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ELECTRONIC PROGRESS

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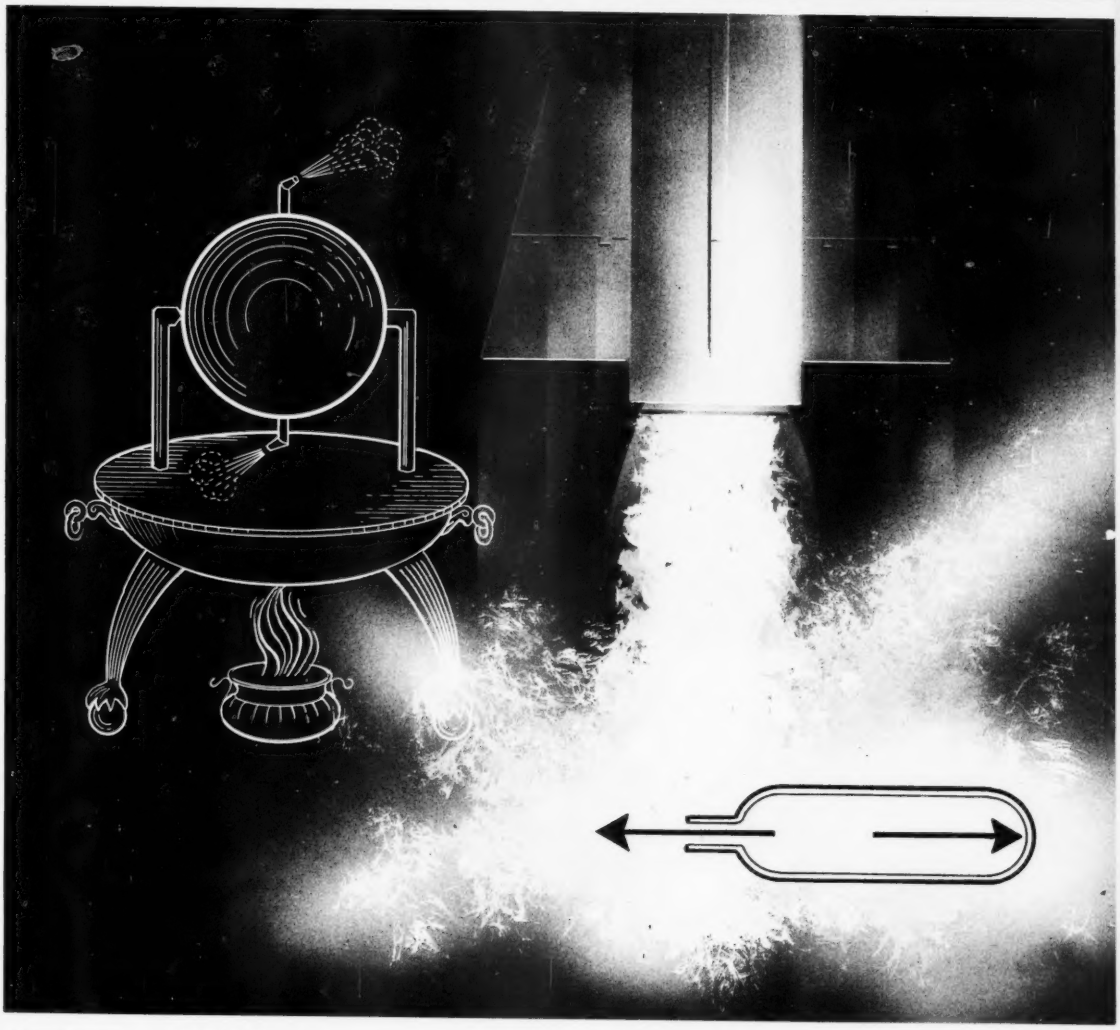

Action and Reaction

In this issue: ROCKET PROPULSION

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Volume III January-February 1959 Number 4

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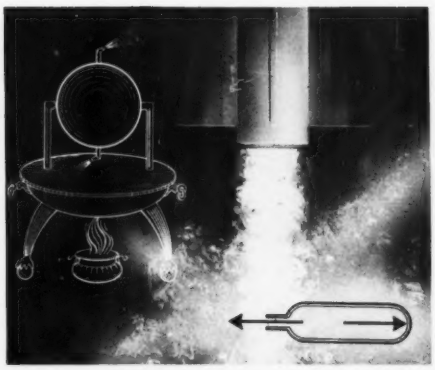

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Calendar

ENGINEERING SEMINARS

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"The Tartar Missile System" J. J. Iffland, Wayland Lab.	Jan. 13	Confidential
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ROCKET PROPULSION

G. A. Ouellette and G. Corey
Bedford Laboratory

THE importance of the rocket motor as a means of propulsion has been increasing steadily in recent years, and will probably continue to do so indefinitely. The rocket motor is by no means a new device. As a matter of fact, it is considered to be the oldest prime-mover known to man, and until the advent of rifling in cannons it played an important role as a weapon of war.

During World War II, rocket powered missiles assumed considerable importance when precision industrial techniques allowed scientists to design short-range missiles whose accuracy almost equalled that of rifled cannons. Following the war, electronic and radar techniques improved the accuracy of rocket propelled missiles to such an extent that they have, for practical purposes, replaced both short and long range artillery. These new techniques have also brought within man's grasp the age-old dream of the conquest of space.

The characteristic of a rocket powered vehicle which enables it to operate even in a vacuum is that it carries its own oxidizer source as well as its fuel, and needs no fixed mass to react against. Its total propellant consumption is much higher than in the case of air-breathing engines since it carries all of the propellants, and it is usually desirable to limit the duration of operation to only a few seconds or minutes. The short operational periods of a rocket are offset by the high power to weight ratio of the engine itself. In general, therefore, a vehicle utilizing rocket propulsion consists of an engine, fuel and oxidizer, structure, and some form of useful load — usually called payload.

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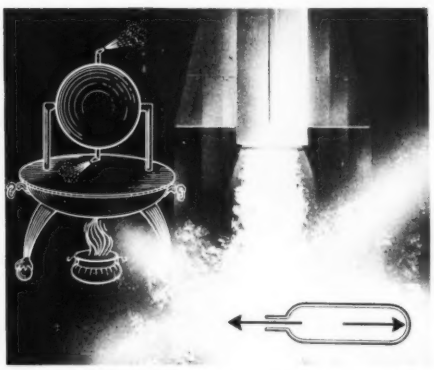

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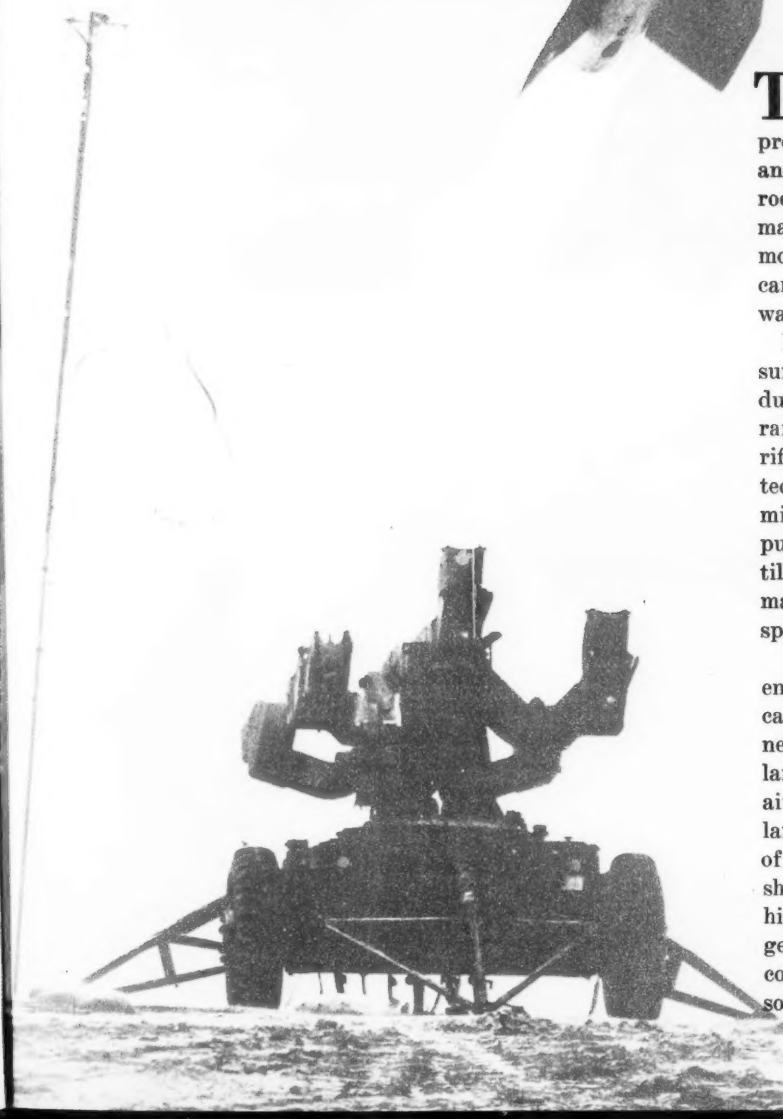

Although all mechanical machines in use today obey the simple laws formulated by Newton, none demonstrate more vividly the principles outlined in his first and third laws than does the rocket engine. The principle of rocket or reaction propulsion is described best by his first law which states that a body at rest will remain at rest, and a body in motion will remain in rectilinear motion unless acted upon by some outside force. On the basis of this law, it can be shown that the center of mass of an isolated system of particles at rest in free space cannot move unless some outside force acts on the system. If some particles in the system are displaced as a result of some phenomena in the system itself, the over-all internal motion must be such that the mass center remains fixed in compliance with the first law.

Extending this explanation to a rocket vehicle in free space where the system consists of the vehicle and its fuel, it is apparent that as fuel is burned, and the combustion products ejected from the vehicle in a given direction, the vehicle itself must move in the opposite direction in a manner such that the center of mass of the system remains fixed in its original position for all time. This is in respect to some fixed inertial one-dimensional coordinate system.

$$x = \frac{\sum_{k=1}^{n} x_k \, m_k}{\sum_{k=1}^{n} m_k} = \text{constant} \quad . \qquad (1)$$

The equation above is the analytical expression of the preceding statement, where (x) is the coordinate of the mass center, (x_k) is the (x) coordinate of the k^{th} particle, and (m_k) is the mass of the k^{th} particle.

Since the particle moves with some finite velocity, Newton's first law leads naturally to his third law which states that linear momentum is conserved, or, for every action there is an equal and opposite reaction. For the rocket, the conservation of linear momentum can be written as:

$$\sum_{k=1}^{n} m_k \, (v_k - v_o) = 0 \qquad (2)$$

where (m_k) and (v_k) are the mass and velocity respectively of the k^{th} particle at any time and (v_o) is the initial velocity of the system, zero in the rest case above. The rocket vehicle structure and unburnt fuel constitute one particle and the ejected gases the other particles.

Applying Equation (2) to a rocket of mass M which is ejecting particles dM at a velocity C relative to the rocket gives the following:

$$\{(M - dM)\,(V + dV) + dM\,(V - C)\} - MV = 0, \qquad (2a)$$

where (V) is the velocity at any time, and $(V + dV)$ is the velocity after dM particles have been ejected. Integrating this equation between some initial mass (M_o) and velocity (V_o) and some final mass (M) and velocity (V) results in the following fundamental equation of rocket propulsion:

$$V - V_o = -C \log \frac{M_o}{M} = -C \log R \quad . \qquad (3)$$

The negative sign prefixing the (C) denotes that it is directed opposite to the direction of motion. The ratio $M_o/M = R$ is called the mass ratio of the rocket vehicle. (R) and (C) completely determine the capabilities of a rocket operating in free space, i.e. in a vacuum with no gravity or other forces acting upon it. Equation (3) showing the dependence of the velocity change on (C) and (R) is plotted in Figure 1, where (V_o) is zero. The final velocity (V) is called the characteristic velocity of the rocket vehicle, and is used as a measure of the vehicle's capabilities.

Any maneuver performed by a rocket vehicle in a gravitational field can be expressed as a change in its intrinsic energy if there are no non-conservative forces acting upon it. The intrinsic energy is, therefore, the sum of its kinetic and potential energies, or:

$$T = Q + V = \frac{1}{2} M v^2 - M g_o \frac{R_o^2}{R} \qquad (4)$$

where the potential energy has its zero reference at an infinite distance from the earth's center, and $(g_o R_o^2/R^2)$ represents the gravitational acceleration at any radial distance $R(>R_o)$ from the center of the earth. This reduces to (g_o) at the earth's surface where $R = R_o$. If a rocket performs some maneuver where a change in energy from condition (1) to condition (2) is involved, this change can be expressed as an equivalent or characteristic velocity (V_c) such that

$$V_c^2 = V_2^2 + 2 g_o R_o^2 \left(\frac{1}{R_1} - \frac{1}{R_2}\right) - V_1^2 \, . \qquad (5)$$

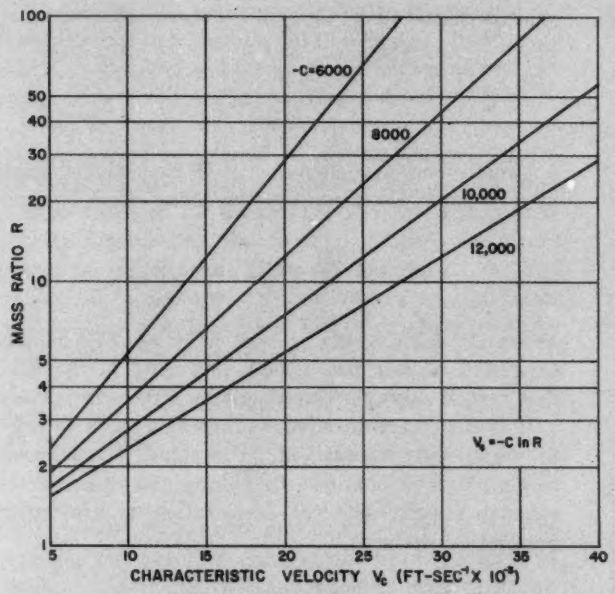

Figure 1

In the case of a vertical sounding rocket attaining some altitude $h = R_2 - R_o$:

$$V_c = \sqrt{2g_oR_o}\ \sqrt{1-\frac{R_o}{R_2}} = U\sqrt{1-\frac{R_o}{R_2}} \quad . \quad (6)$$

It is interesting to note that as (R_2) approaches an infinite value, (V_c) asymptotes to a finite value $U = \sqrt{2g_oR_o}$ (approximately 6.95 miles per second). If a rocket vehicle is accelerated to this velocity U at the surface of the earth in any direction above the horizontal, it will have sufficient energy to "escape" from the earth's gravitational attraction, and never return. In practice, however, this value of U must be modified to allow for frictional losses due to air resistance on the vehicle, and to potential losses due to finite acceleration times when work is done lifting unburnt fuel against the earth's potential field.

For a satellite vehicle in a circular orbit, Equation (5) becomes:

$$V_c = U\sqrt{1-\frac{R_o}{2R}} \qquad (7)$$

where (R) is the radius of the satellite orbit from the geocenter. Equations 6 and 7 are plotted in Figure 2.

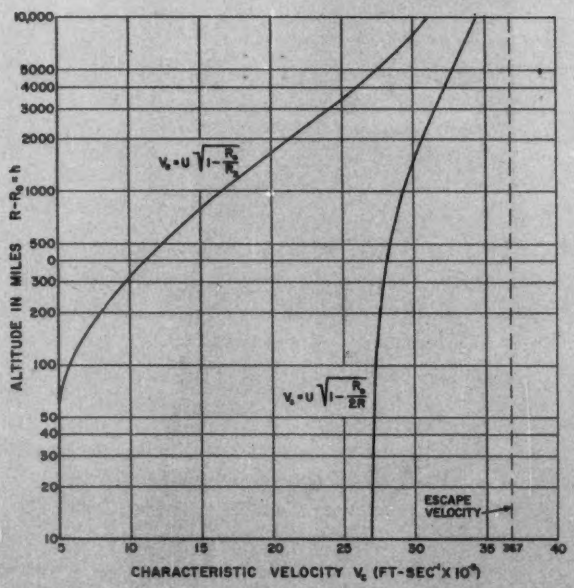

Figure 2

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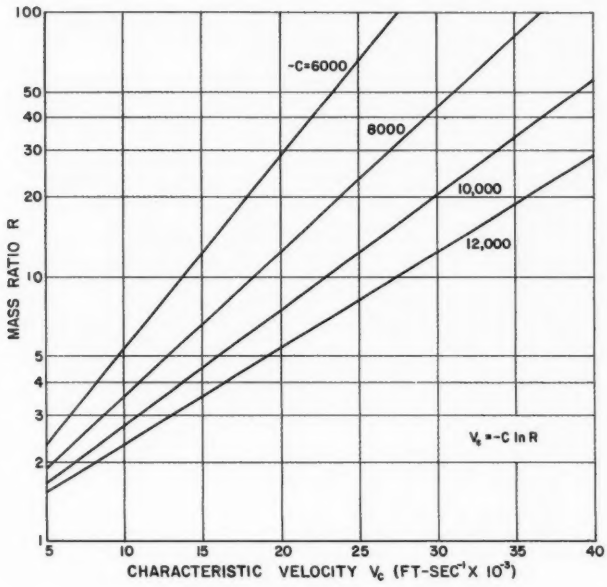

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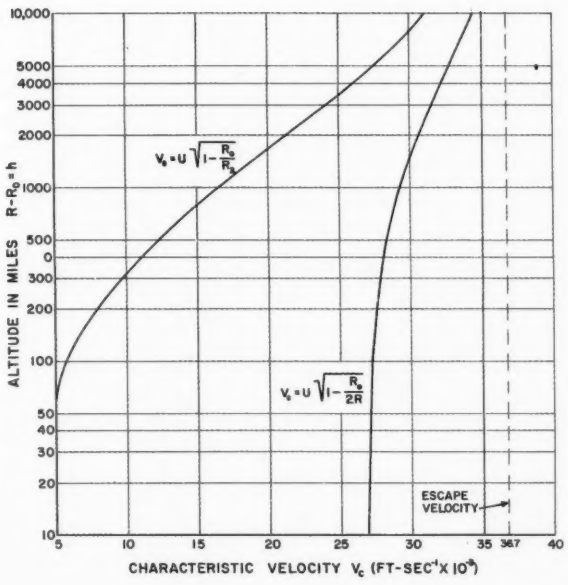

Figure 2

Rocket motors at the present time are used primarily by the military as propulsion devices for guided weapons, and for extra thrust in aircraft, although space vehicles and rocket aircraft are becoming increasingly important. Basically, a rocket motor (or engine) consists of a thrust chamber into which the fuel and oxidizer are injected and combusted, and a nozzle for expanding the ejected gases.

Rocket motors in use today are classified into two catagories:

1. The liquid rocket "engine"
2. The solid rocket "motor"

The terms engine and motor usually refer to liquid and solid propellant units respectively. The motors are shown in Figure 3.

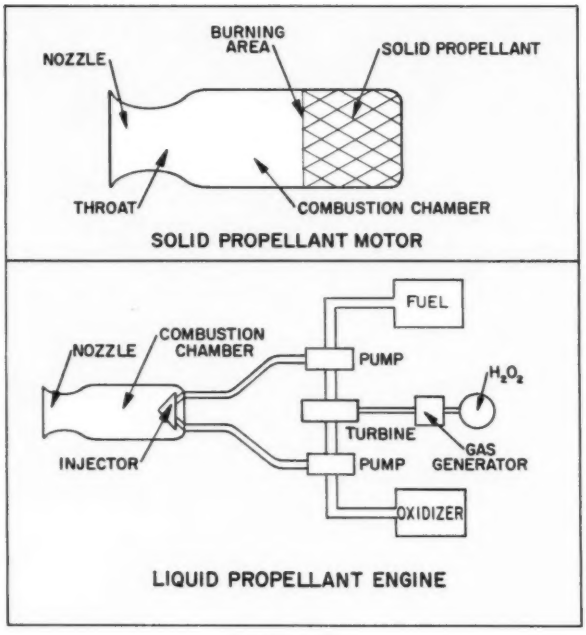

Figure 3

The liquid rocket employs separate fuel and oxidizer tanks together with appropriate pumps (unless pressurized tanks are used) and flow control valves to insure proper oxidizer to fuel ratio. The fuel and oxidizer are introduced into the combustion chamber and ignited to produce the high pressure gases that are expanded out the nozzle of the engine. The solid rocket, on the other hand, consists of a homogeneous mixture of fuel and oxidizer which is cured into a solid mass. This solidified propellant may be "cartridge-loaded" into a rocket chamber or the fuel-oxidizer mixture may be poured directly into the chamber and then cured to a solid. The latter is referred to as a "case-bonded" rocket motor.

The thrust or force that a rocket engine exerts is given by Newton's second law which states that force is proportional to the time rate of change of momentum as

$$F = \frac{d}{dt}(MV) \quad . \tag{8}$$

Usually the particle velocity of the exhaust gases of a rocket is constant, and the thrust force becomes

$$F = C\frac{dM}{dt} = C\dot{M} \text{ (pounds)} \quad , \tag{8a}$$

where (C) is called the exhaust or jet velocity, usually expressed in feet per second, and ($\dot{M}$) is the mass flow rate in slugs per second, giving a force in pounds.

It is customary in missile propulsion work to refer to the specific impulse (I_{sp}) developed by a rocket motor. This is obtained by taking the ratio of the exhaust velocity and the acceleration of gravity at the earth's surface.

$$I_{sp} = \frac{C}{g_o} \text{ (seconds)} \tag{9}$$

The I_{sp} is given in seconds and represents the period of time that any given amount of fuel can support itself against gravitational force with no relative motion before being burned up. The total impulse (I_t) is the product of the thrust level and the duration (t) of thrust,

$$I_t = Ft \text{ (lb-sec)} \tag{10}$$

and is expressed in pounds-seconds. If the thrust level varies as a function of time (caused by variations in atmospheric conditions which can be related to time) the total impulse is

$$I_t = \int_{t_o}^{t} F(t)dt \text{ (lb-sec)} \quad . \tag{10a}$$

For any type of rocket engine the exhaust velocity is given by

$$C = \sqrt{\frac{2\gamma}{(\gamma-1)}\frac{RT_o}{M}g_o\left\{1-\left(\frac{P_x}{P_o}\right)^{(\gamma-1)/\gamma}\right\}} \text{ (ft/sec)} \tag{11}$$

where γ is the ratio of specific heats of the exhaust gas R is the universal gas constant in ft-lb/ lb mol/°C, T_o is the combustion temperature in °K, M is the molecular weight of exhaust, and P_x/P_o is the ratio of exit pressure to chamber pressure.

From this expression it is apparent that gases of low molecular weight M, or high calorific value $(\gamma/\gamma-1)(RT_o/M)$ are desirable for high values of C. Note also that in a vacuum with no ambient back pressure P_x is minimal and the efficiency of the engine is at a maximum for a given calorific value of the fuel.

When a rocket vehicle operates in a gravitational field, and for some period of time in an atmosphere, the characteristic velocity equation (3) is still used as a measure of its capability; but the actual final velocity attained by the rocket is a function of its thrust to weight ratio and air resistance. On the average, it is expected that the maximum characteristic velocity required by a large sounding or space rocket would be approximately

$$V_c = V_o \sqrt{\frac{(F/M)}{(F/M)-g_o}} + eV_o \qquad (12)$$

for values of F/M greater than 2, where (V_o) is the required maneuver velocity given by Equation (6) (called V_c there), F/M is the thrust to mass ratio (assumed constant) and g_o is the acceleration of gravity (assumed constant during the period of powered flight). The first term on the right side of Equation (12) accounts for the work done in carrying unburnt fuel up in the gravitational field, and the second term accounts for the losses due to air resistance where (e) assumes a value somewhere between 0.05 and 0.1 for large sounding or space rockets. The best compromise involves an initial, almost impulsive, acceleration to some velocity (v) such that $mg = (1 + v/c)D$, followed by a thrust force such that this relation is held throughout the burning period rather than burning all the fuel as fast as possible to minimize the potential work. In this last relationship (D) is the aerodynamic drag force, and (m), (g), (v) are instantaneous values of rocket mass, gravity, and velocity, and (c) is the exhaust velocity. Although Equation (12) was determined under constant conditions it still holds approximately in the optimum case.

Having considered the simple laws of rocket motion in gravitational fields, and for zenithal trajectories, it is now possible to discuss the problems relating to the general principles of rocket motor efficiencies and power.

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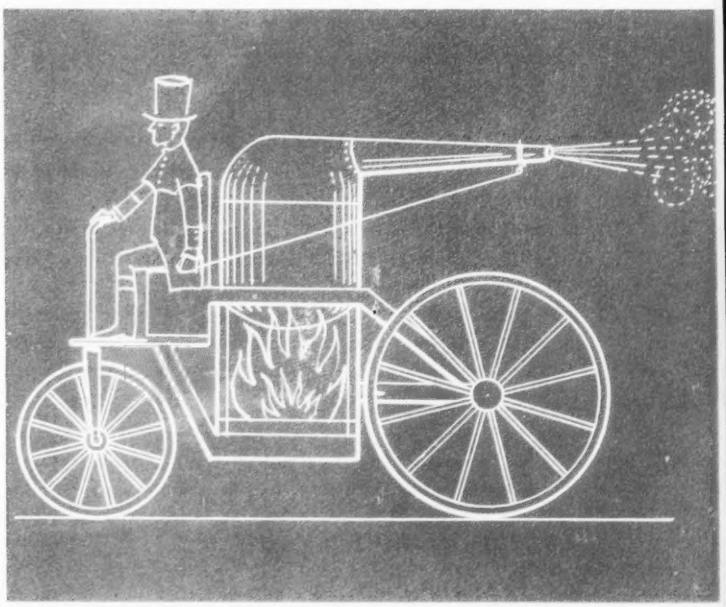

Rocket motors at the present time are used primarily by the military as propulsion devices for guided weapons, and for extra thrust in aircraft, although space vehicles and rocket aircraft are becoming increasingly important. Basically, a rocket motor (or engine) consists of a thrust chamber into which the fuel and oxidizer are injected and combusted, and a nozzle for expanding the ejected gases.

Rocket motors in use today are classified into two catagories:

1. The liquid rocket "engine"
2. The solid rocket "motor"

The terms engine and motor usually refer to liquid and solid propellant units respectively. The motors are shown in Figure 3.

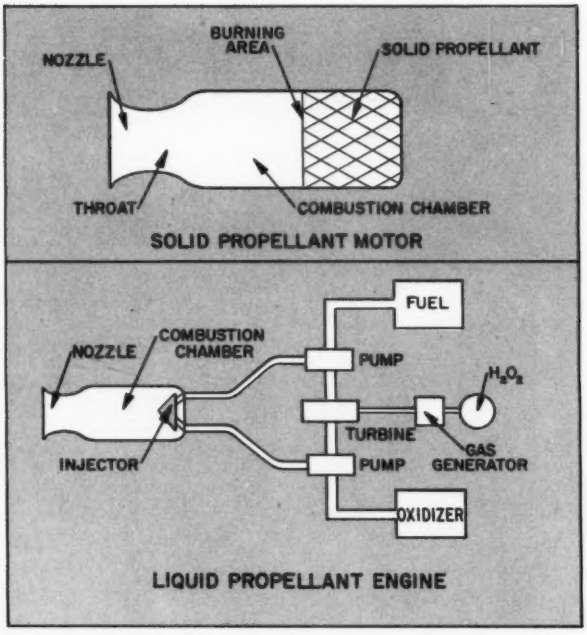

Figure 3

The liquid rocket employs separate fuel and oxidizer tanks together with appropriate pumps (unless pressurized tanks are used) and flow control valves to insure proper oxidizer to fuel ratio. The fuel and oxidizer are introduced into the combustion chamber and ignited to produce the high pressure gases that are expanded out the nozzle of the engine. The solid rocket, on the other hand, consists of a homogeneous mixture of fuel and oxidizer which is cured into a solid mass. This solidified propellant may be "cartridge-loaded" into a rocket chamber or the fuel-oxidizer mixture may be poured directly into the chamber and then cured to a solid. The latter is referred to as a "case-bonded" rocket motor.

The thrust or force that a rocket engine exerts is given by Newton's second law which states that force is proportional to the time rate of change of momentum as

$$F = \frac{d}{dt}(MV) \quad . \qquad (8)$$

Usually the particle velocity of the exhaust gases of a rocket is constant, and the thrust force becomes

$$F = C\frac{dM}{dt} = C\dot{M} \text{ (pounds)} \quad , \qquad (8a)$$

where (C) is called the exhaust or jet velocity, usually expressed in feet per second, and ($\dot{M}$) is the mass flow rate in slugs per second, giving a force in pounds.

It is customary in missile propulsion work to refer to the specific impulse (I_{sp}) developed by a rocket motor. This is obtained by taking the ratio of the exhaust velocity and the acceleration of gravity at the earth's surface.

$$I_{sp} = \frac{C}{g_o} \text{ (seconds)} \quad . \qquad (9)$$

The I_{sp} is given in seconds and represents the period of time that any given amount of fuel can support itself against gravitational force with no relative motion before being burned up. The total impulse (I_t) is the product of the thrust level and the duration (t) of thrust,

$$I_t = Ft \text{ (lb-sec)} \qquad (10)$$

and is expressed in pounds-seconds. If the thrust level varies as a function of time (caused by variations in atmospheric conditions which can be related to time) the total impulse is

$$I_t = \int_{t_o}^{t} F(t)dt \text{ (lb-sec)} \quad . \qquad (10a)$$

For any type of rocket engine the exhaust velocity is given by

$$C = \sqrt{\frac{2\gamma}{(\gamma-1)}\frac{RT_o}{M}g_o\left\{1-\left(\frac{P_x}{P_o}\right)^{(\gamma-1)/\gamma}\right\}} \text{ (ft/sec)} \qquad (11)$$

where γ is the ratio of specific heats of the exhaust gas R is the universal gas constant in ft-lb/ lb mol/°C, T_o is the combustion temperature in °K, M is the molecular weight of exhaust, and P_x/P_o is the ratio of exit pressure to chamber pressure.

From this expression it is apparent that gases of low molecular weight M, or high calorific value $(\gamma/\gamma-1)(RT_o/M)$ are desirable for high values of C. Note also that in a vacuum with no ambient back pressure P_x is minimal and the efficiency of the engine is at a maximum for a given calorific value of the fuel.

When a rocket vehicle operates in a gravitational field, and for some period of time in an atmosphere, the characteristic velocity equation (3) is still used as a measure of its capability; but the actual final velocity attained by the rocket is a function of its thrust to weight ratio and air resistance. On the average, it is expected that the maximum characteristic velocity required by a large sounding or space rocket would be approximately

$$V_c = V_o \sqrt{\frac{(F/M)}{(F/M)-g_o}} + eV_o \qquad (12)$$

for values of F/M greater than 2, where (V_o) is the required maneuver velocity given by Equation (6) (called V_c there), F/M is the thrust to mass ratio (assumed constant) and g_o is the acceleration of gravity (assumed constant during the period of powered flight). The first term on the right side of Equation (12) accounts for the work done in carrying unburnt fuel up in the gravitational field, and the second term accounts for the losses due to air resistance where (e) assumes a value somewhere between 0.05 and 0.1 for large sounding or space rockets. The best compromise involves an initial, almost impulsive, acceleration to some velocity (v) such that $mg = (1 + v/c)D$, followed by a thrust force such that this relation is held throughout the burning period rather than burning all the fuel as fast as possible to minimize the potential work. In this last relationship (D) is the aerodynamic drag force, and (m), (g), (v) are instantaneous values of rocket mass, gravity, and velocity, and (c) is the exhaust velocity. Although Equation (12) was determined under constant conditions it still holds approximately in the optimum case.

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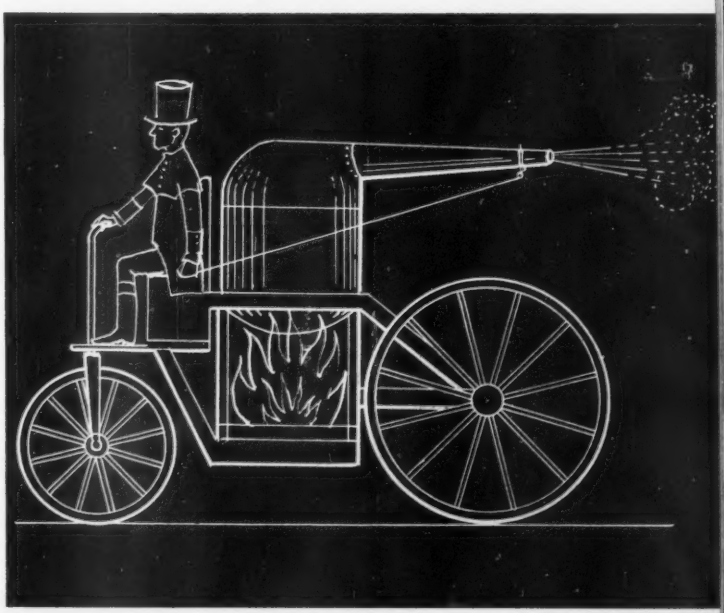

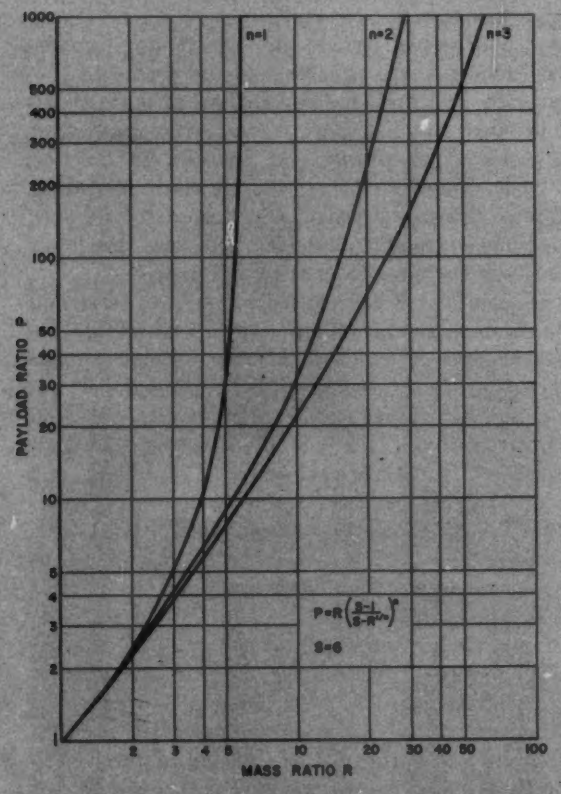

Figure 4

velocities of about 16,900 ft/sec. Inspection of Equation (6) clearly shows the impossibility of using a single-stage rocket for space operations at this time, since this is far short of the 36,700 ft/sec required to "escape" from the earth's gravitational field.

It is readily apparent from the basic rocket equation (3) that characteristic velocities are additive, which suggests the possibility of using more than one rocket to do a given job, i.e. multi-staging. In this case, Equation (3) becomes

$$V_c = -C_1 \log R_1 - C_2 \log R_2 - \ldots - C_n \log R_n; \qquad (13)$$

or if all the C's and R's are equal

$$V_c = -C \log R^n. \qquad (13a)$$

Although multi-staging overcomes the problem of small mass ratios, it imposes a staggering weight penalty on the over-all rocket vehicle since (V_c) goes up only as the log of R, but until larger values of C are available there is no alternative. For satellite vehicles, the initial weight is from one to three thousand times the useful payload weight, as in the case of the Vanguard or Explorer rockets. This payload ratio is readily calculable from the equation

$$P = R\left(\frac{S-1}{S-R^{1/n}}\right)^n , \qquad (14)$$

where (R) is the mass ratio required to attain some characteristic velocity obtainable from Equation (3), S is the structural ratio of each stage (ratio of structure plus fuel to structure alone), and (n) is the number of stages. For the Vanguard rocket (R) and (S) are in the vicinity of 35 and 5 respectively. Equation (14) is plotted in Figure 4 for an S of 6, and an (n) of 1, 2, and 3. It should be noted that a single-stage rocket always has a greater take-off mass than a multi-stage rocket for the same all-burned velocity, if such a single-step rocket could be built.

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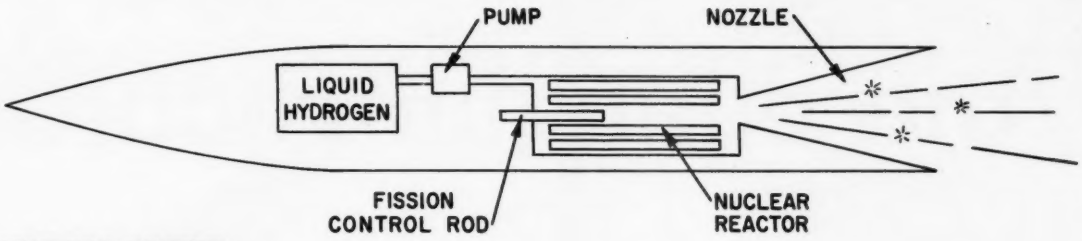
New concepts in propulsion will probably reduce or eliminate the need of multi-staging techniques, except that some form of jet booster may be utilized to lift nuclear powered rockets up to an altitude where radiation poses little hazard before the main drive is initiated. There are several types of reaction propulsion systems that show promise, some providing high thrust levels suitable for planet falls, such as the nuclear rocket, and others utilizing low thrust levels suitable for deep space operations with take-off from a satellite orbit, such as the ion rocket.

The vistas opened by rocket propulsion are many and diversified, from well-drilling apparatus to space flight, from ship-board rescue devices to war machines. But no matter what the specific use may be, it relies on the ability of a rocket vehicle to react against itself, completely eliminating the need of some external environment as required by all other types of prime-movers.



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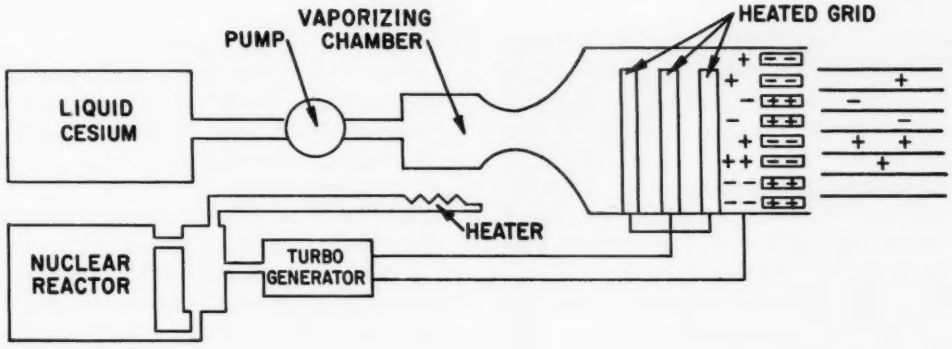

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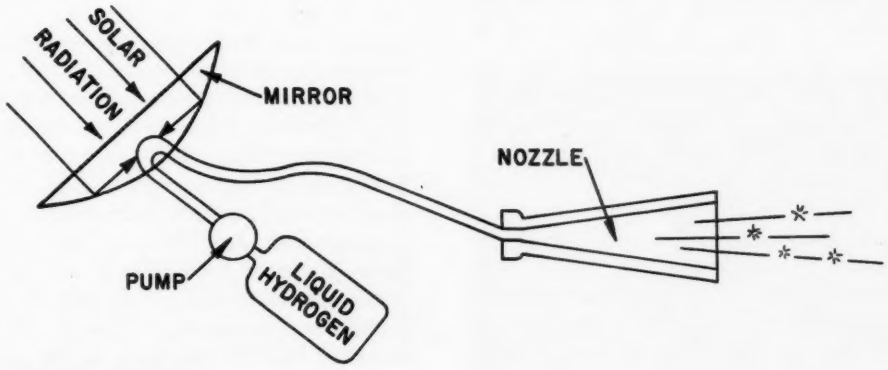

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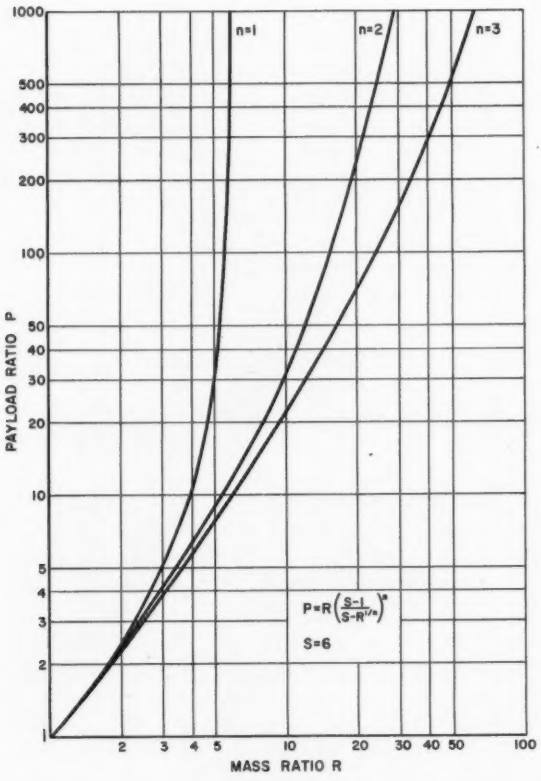

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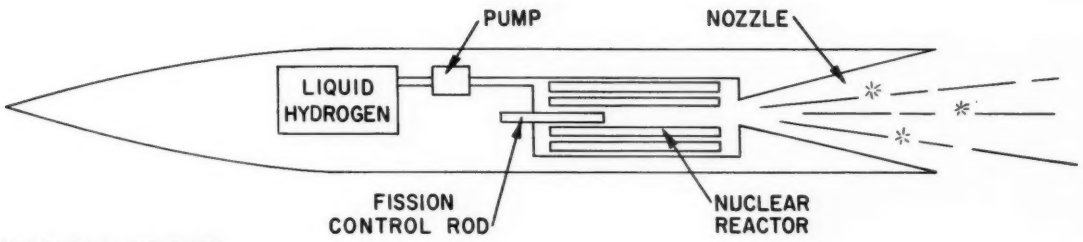

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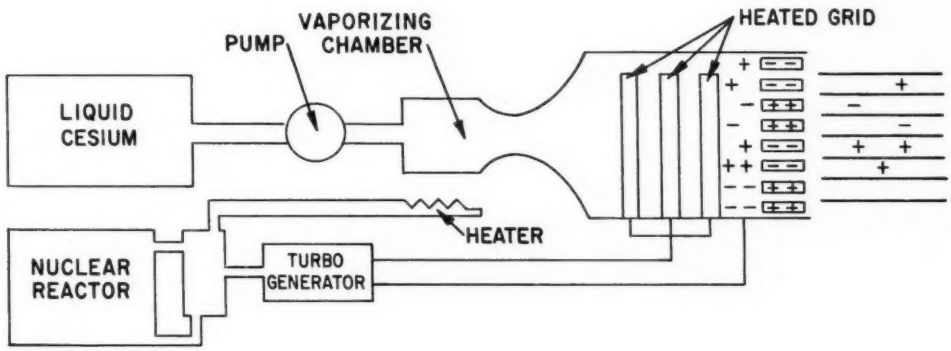

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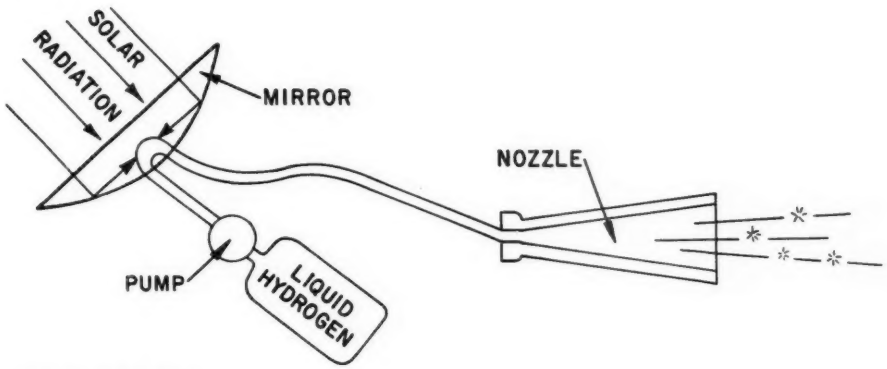

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the dual-gun recording

A. S. Luftman
Microwave and Power Tube Division

SINCE the invention of the Recording Storage Tube by R. C. Hergenrother and B. C. Gardner in 1948, the design has passed through many stages and phases. In the early experiments, both direct view and electronic output tubes were designed in types using from one to three electronic guns. Raytheon decided in 1950 that it would specialize in the most versatile type — the single gun electronic output version — for commercial production. Though each of the basic storage-tube types presently being sold was invented a decade ago, the era of the storage tube is just beginning.

Continuing improvements in such characteristics as the resolution (or amount of detail that can be stored) and the accuracy in reproduction of shades of gray have vastly increased the number of applications for storage tubes. Some of the most important advances made in the design of the Recording Storage Tube were described in detail in articles published between 1950 and 1956.[1, 2, 3] The latest innovation, however, is perhaps the most dramatic and useful of them all. This development is, in brief, an improvement in the resolution of Recording Storage Tubes from 600 lines per diameter to 1000 lines per diameter, along with marked improvements in other characteristics such as background uniformity.

What are some of the important applications for such storage tubes? The article entitled "Electronic Plotting of Moving Targets" (September-October 1957 issue of ELECTRONIC PROGRESS) described an equipment designed to convert a radar picture into a constant brightness display wherein moving targets appeared as typical radar returns, but with long trails behind them showing their history. Many other applications have added to the importance of the storage tube as a basic component in radar systems. Among these must be included typical scan-conversion of PPI radar information into a television-type raster scan for display on commercial monitors, slow scanning of stored radar or TV type pictures to reduce the bandwidth of their frequency components and permit retransmittal of the pictures over narrow-band communication lines such as commercial telephone circuits, and applications where it is desired to store radar for one antenna rotation and then use the stored picture for navigation.

The current requirement for storage tubes which has received most emphasis has been to make flying safer by means of effective air traffic control. For this application it is desired to store radar pictures simultaneously from more than one source, show target trails for the moving airplanes, scan-convert the radar picture into TV, and then display the television image on a large number of monitors. It is necessary that the storage device be able to *simultaneously* write radar information and transmit or read out the stored TV pictures. The resolution of the storage device and, in fact, of the whole system must be as high as possible, to permit storing a large area on the indicator and yet be able to separate aircraft that are relatively close together. With the CAA requirements in mind and the knowledge that there were many similar applications, Raytheon began a company-sponsored program to redevelop a dual-gun Recording Storage Tube fundamentally similar to the ones made in the earliest days of storage tubes but with sufficient resolution, background uniformity, and control of erasure characteristics to make the proposed radar-display system practical.

Fortunately, a parallel development project had been in process for several months aimed at improving the basic single gun Recording Storage Tube to have 1000 lines resolution and other desired characteristics. Thus, with the advantages of ten years experience in storage tube design, the newly developed cathode ray electron gun suitable for producing 1000 lines resolu-

tube

tion on a storage screen, and a newly perfected collimation lens system capable of minimizing background shading or non-uniformity to 10% of peak amplitude signals, Raytheon was able to produce a high resolution scan-converter storage device within only a few short months of the date the project was initiated.

An indication of what is actually meant by a resolution (measured, according to IRE Standards, at 50% output level) of 1000 TV (or black and white) lines is seen in the three-step series of photographs labelled Figure 1. The first photograph in this series shows a test pattern which has been stored in a Recording Storage Tube and is being played back onto a typical TV monitor. In the second photograph we can see that the pattern was, in fact, stored on only a small area of the total storage screen. The resolution across a diameter of the storage tube is, therefore, the resolution across the stored pattern times the ratio of the usable storage tube diameter to the portion of the diameter actually used in a horizontal direction. In the third photograph of the series, we have blown up the central area of the same stored picture to show that the lines in the vertical wedges can actually be resolved down to the base circle. (The converging lines are a measure of resolution, and the numbers beside the wedge pattern, such as 35 and 45, indicate a resolution of 350 lines and 450 lines respectively, if they can be distinguished as separate lines.) The fact that we can resolve lines right down to the base circle indicates that 500 lines could be resolved in the size of the stored picture or that well over 1000 TV lines can be resolved across the diameter of the stored surface. (The photographs shown were taken using a single gun kiloline Recording Storage Tube since adequate equipment to run this test was not available for the dual-gun tube at that time. Were the equipment available, the same test results would have been obtained with the dual-gun tube.)

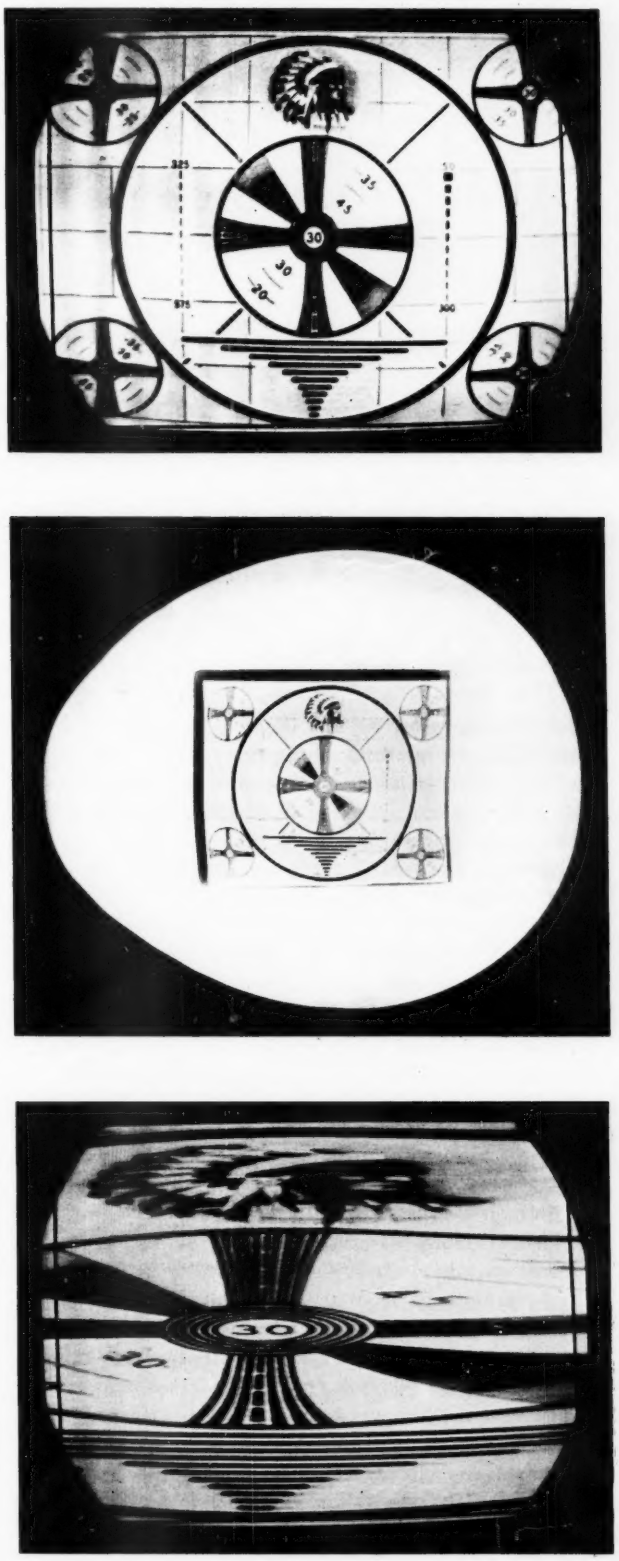


Figure 1

Figure 2

The photographic series of Figure 2 shows a picture stored from a live television broadcast and then played back to the TV monitor and photographed. Again we see that only a portion of the storage tube area was required to store television quality pictures. More important, however, we can see that the gray shades in the television picture were maintained. It should be noted here that the Recording Storage Tube does not merely stop the action of the picture and then allow the stored image to be played back once, but can play back the stored image thousands of times without substantial deterioration. Moreover, the stored picture can be held for periods of hours prior to retransmittal. Now with an understanding of some of the more dramatic capabilities of such storage devices, perhaps a brief explanation of the theory of operation is desired.

Typically, a three- or four-step cycle is used in the operation of recording tubes. When a four-step cycle is desired, the steps are erase, prime, write and read. For the three-step cycle the functions of erase and prime are combined for circuit simplicity, though at a slight loss in the degree of erasure which can be obtained. During the erase, prime, and write modes of operation, an electron beam from a gun is used to vary the charge level on the storage surface, while during read, the charge pattern previously written amplitude modulates a constant beam from a gun. (Naturally, the electron beam is being scanned during these operations.)

In Figure 3 we see a typical secondary-emission curve of a dielectric surface. Along the horizontal axis is plotted the velocity of electrons striking the surface or, by simple conversion, the voltage of that surface. In the vertical axis the secondary emission ratio (or ratio of the number of electrons which bounce off the dielectric surface to the number of electrons which strike it) is plotted. Below a certain value of voltage called the "critical potential," each electron striking drives off, on the average, less than one secondary electron and so the surface being struck would be charged negatively. On the other hand, if the dielectric surface of the storage screen is above critical potential, each electron striking knocks off more than one secondary electron. The surface will therefore charge in a positive direction as long as the voltage field directly before that surface is sufficiently positive to draw off the secondary electrons thus emitted.

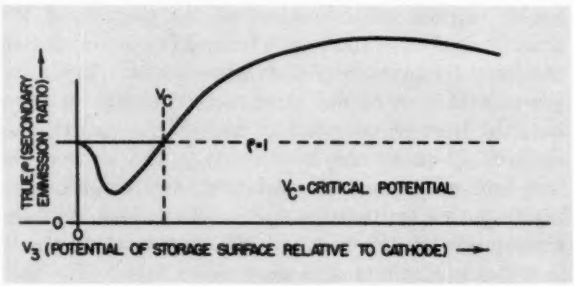
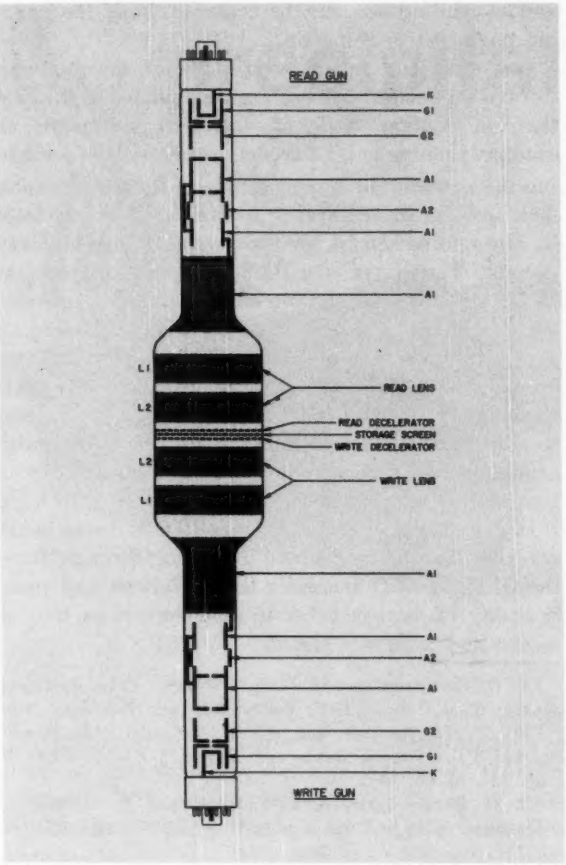


Figure 3

Utilizing this phenomenon of being able to charge either positively or negatively depending upon the dc voltage of the storage surface, we can now cycle the tube through its various modes.

In Figure 4 we can see a schematic representation



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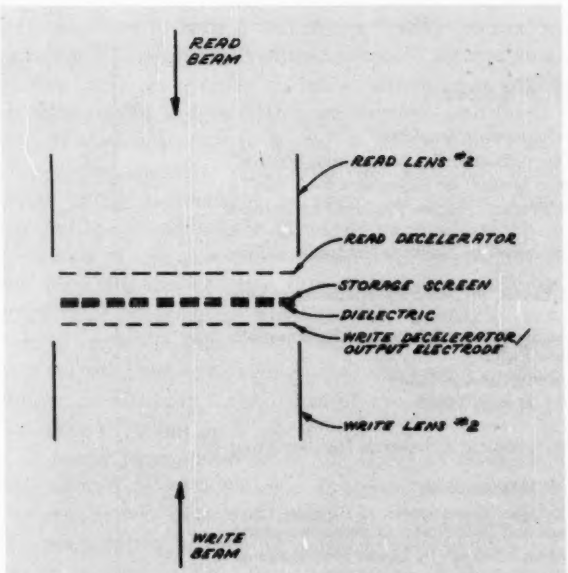

Figure 5

of the QK703 dual-gun tube. In an expanded view of the storage assembly (Figure 5) we can see that it is made up of three fine mesh (750 wires per inch) screens. The center screen is coated on one side with a thin layer of dielectric capable of holding an impressed charge for many hours without leakage. The electron gun facing the dielectric surface is used for writing and erasing operations, whereas the gun on the opposite side is used for reading the stored picture. As is true in the single-gun tube, priming can be accomplished by setting the storage screen voltage so that it is below critical potential with respect to the writing-gun cathode. Thus, each electron striking the surface will charge that surface negatively towards cathode potential. To switch the tube to a writing mode, it is necessary either to switch the storage screen positively above critical potential or conversely, to lower the cathode potential of the writing gun to a point where the storage screen is above critical potential with respect to this writing gun cathode. With the writing beam modulated by a typical signal and scanned in a radar or TV type pattern, a complete picture can be "painted" onto the storage surface or, in other words, stored.

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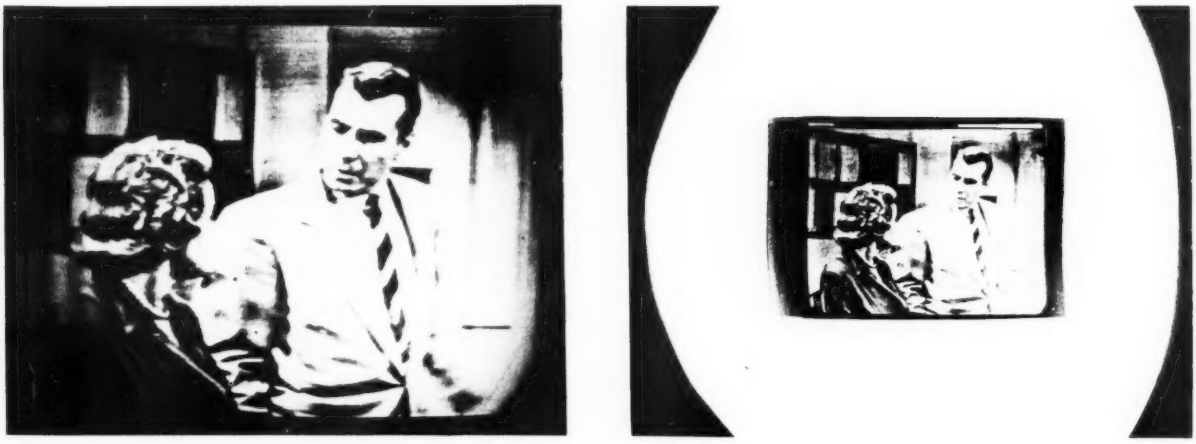
It can be readily understood that, though a signal is being impressed on the output screen from the reading beam, a portion of the writing beam also strikes this screen. If no provisions were made to separate these two signals, the output developed from the two currents impinging on the screen would result in what is called "cross-talk." To permit separation of the writing and reading video signals, the reading beam is modulated with a high frequency carrier,



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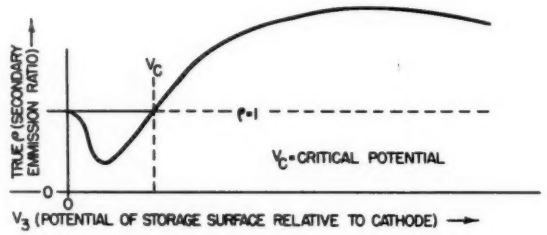

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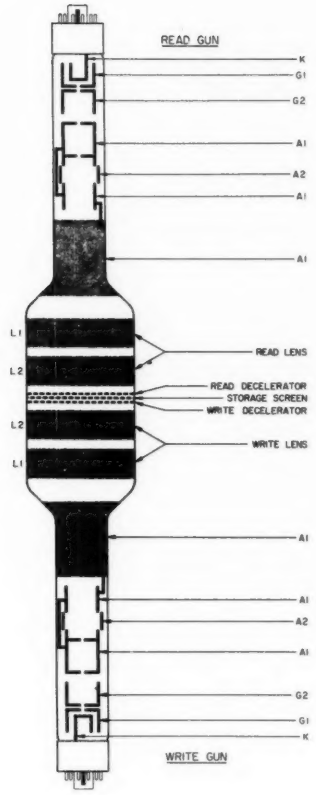

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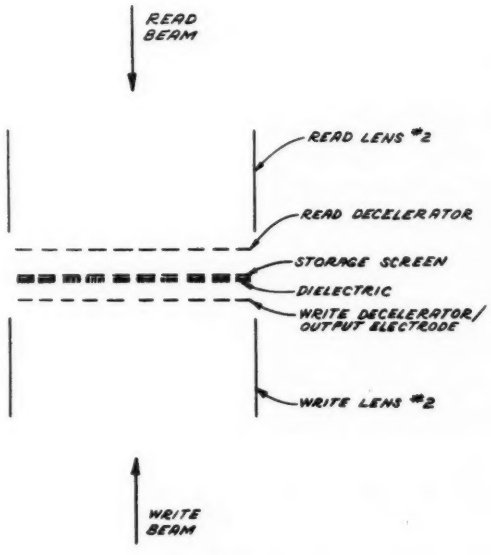

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perhaps 30 megacycles. When the output is then fed through an IF amplifier tuned to the carrier frequency, only those signals developed by the reading beam can pass through this amplifier, and effective discrimination against the writing signal is accomplished.

Though the single-gun kiloline Recording Storage Tube was, in itself, a remarkable advance in the state of the art, the dual-gun type has additional advantages. First, we see that reading can be performed at all times, even when new video signals are being written. Moreover, it is never necessary to switch the storage screen potential. (In single-gun types, a basic problem results from the fact that the switching of the storage screen voltage provides transients in the output electrode signal.) When it is desired to partially or totally prime the storage tube using the write gun, only the writing gun voltages need be shifted and so reading can still be achieved while the priming operation is going on.

One especially important feature of the dual-gun storage tube which has not been mentioned is the fact that, in another mode of operation, automatic or gradual priming can be accomplished without switching the potential on any electrode in the storage tube. This automatic erasure is continuously controllable in rate and so can be used to gradually decay stored signals. Target trails will then appear brightest at the target's present position and will get progressively dimmer in the direction of past history. Thus, in an application where this phenomenon can be utilized, even the mode-switching to accomplish prime is made unnecessary and so the tube can be used for continuous uninterrupted writing and reading with gradual erasure being effortlessly accomplished at a controllable rate.

It is expected that the combination of these many valuable features in a single Recording Storage Tube, the QK703, vastly increases the usefulness and practicability of storage tubes to scan-convert as well as record and integrate signals.

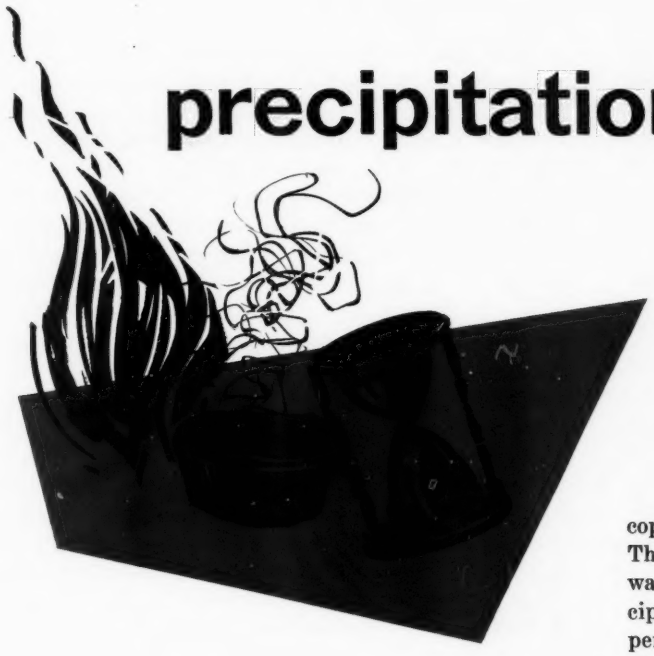
[1] R. C. Hergenrother and B. C. Gardner, "The Recording Storage Tube," Proc. IRE, Volume 38, page 740, July 1950.

[2] R. C. Hergenrother and A. S. Luftman, "Single-Gun Storage Tube Writes, Reads and Erases," ELECTRONICS, page 126, March 1953.

[3] R. C. Hergenrother, A. S. Luftman and C. E. Sawyer, "Improved Storage Tube Design," ELECTRONIC INDUSTRIES, page 82, March 1956.

Publications & Papers

D. L. Bobroff	"High Sensitivity Parametric Amplifiers"
A. H. Cross	"A Self-Improvement Program for Engineering Writers"
L. H. Holway, Jr.	"A Fictitious Source Method for Eigenvalue Problems"
T. F. Hueter and W. J. Fry	"Central Nervous System Changes Produced by Focused Ultrasound"
C. A. Klein	"Charge-Carrier Removal in Neutron-Irradiated p-Type Silicon"
C. A. Klein and W. D. Straub	"On the Energy Levels in Neutron-Irradiated p-Type Silicon"
G. F. Koster and H. Statz	"A Method of Treating Zeeman Splittings of Paramagnetic Ions in Crystalline Fields"
A. S. Luftman	"A Survey of Recording Storage Tubes"
A. S. Luftman and C. H. Sawyer	"Kiloline Recording Storage Tube"
R. Martinengo	"Considerations in Transistor Automobile Receiver Front End Design"
H. L. Myers	"Riding Herd on 2500 Metal Alloys"
G. Rupprecht	"Pulsed Field-Effect for Measurement of Capture Cross Section of Surface and Bulk States in Semiconductors"
G. Sandler	"Maximum Inspection Efficiency by Linear Programming"
T. C. Taylor	"Technique for Making Crack-Free Alloyed Junctions in Silicon"
G. V. Woodley	"Analogue Simulation of Networks"



precipitation HARDENING of metals

F. C. Hawkes
Research Division

THE first known example of "age-hardening" was observed more than fifty years ago by Alfred Wilm in Germany. Wilm was experimenting with copper-bearing aluminum alloys for use in Zeppelin dirigibles when he observed that the hardness increased on standing at room temperature after a high temperature heat-treatment. The details of composition and heat-treatment were worked out for an alloy known as duralumin (four percent copper, one-half percent magnesium and manganese, balance aluminum) which combined light weight with high strength and ductility. If such an alloy is heated to about 500°C and then cooled rapidly, it is relatively soft and weak. After aging at room temperature for several days, the hardness and tensile strength have significantly increased. It is now known that other properties of the alloy are also changed during the aging process; Wilm and other early workers were primarily concerned with the increase in hardness and therefore applied the term age-hardening to the process. Duralumin, incidentally, is still one of the most useful of the wrought aluminum-base alloys.

A tentative explanation of the aging of duralumin was offered in 1919. It was proposed that much of the copper was dissolved in the aluminum matrix at the temperature of the initial heat-treatment (500°C). Rapid cooling resulted in the retention of the copper in supersaturated solution. This solution was unstable and tended to decompose slowly at room temperature by the precipitation of copper or a compound of copper and aluminum from the aluminum matrix. The observed increase in hardness and other properties was then attributed to the formation of a fine precipitate dispersed throughout the alloy. This theory permitted the generalization of age hardening to all solid-solution type alloys containing a constituent whose solubility decreased with decreasing temperature. The novel characteristic of duralumin was that the precipitation occurred at room temperature at a sufficiently rapid rate for practical purposes. With the help of this generalization, a large number of metals in addition to aluminum have been made precipitation-hardenable by the addition of a suitably chosen metal or metallic compound. Many of these hardenable alloys are aged at elevated temperatures. For this reason and because it better describes the processes involved, the term "precipitation hardening" has often been used to describe the treatment of these special alloys.

The general principles involved in the precipitation process can be illustrated by a relatively simple example involving a familiar alloy — sterling silver. This alloy contains 92.5 percent silver and 7.5 percent copper and is a precipitation-hardening alloy. The partial phase diagram in Figure 1 describes the silver-rich portion of the silver-copper system. This diagram indicates that the solubility of copper in silver decreases from about 8.4 percent at 780°C to less than one percent at room temperature. If the alloy containing 7.5 percent copper is cooled slowly from 780°C, copper will begin to precipitate at about 760°C and will continue to do so as the temperature is lowered to room level. If, however, the same alloy is cooled rapidly from 780°C, the excess copper will remain in solution and a supersaturated solution will result at room temperature. Reheating of the quenched alloy to a temperature within a few hundred degrees of the solubility line, i.e., 300 to 750°C, will cause precipitation of excess copper as small particles, giving

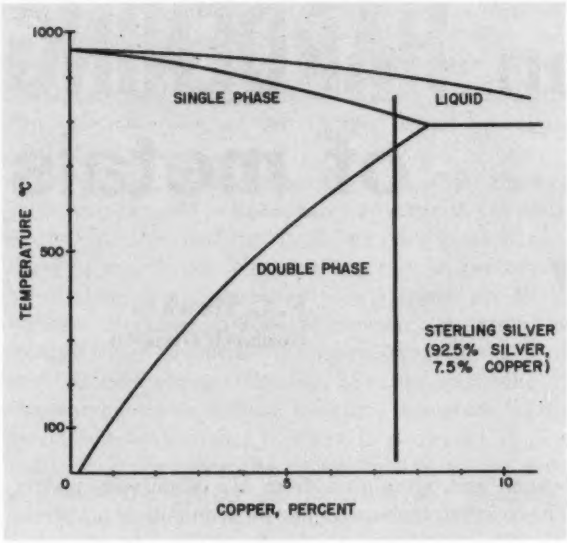


Figure 1

rise to increased hardness. For a given precipitation-hardening temperature, there will be a time at which the maximum hardness is achieved. If this time is exceeded, the precipitated particles coalesce and the hardness is decreased. The time for maximum hardness is shortened as the precipitation temperature is increased. Table 1 illustrates the effect of precipitation hardening on sterling silver.

Table 1

Treatment	*Brinell Hardness*
Slow cool from 780°C	70
Quench from 780°C	55
Quench from 780°C plus one-half hour at 300°C	110
Quench from 780°C plus one-half hour at 500°C	75

It is seen that the alloy is softest after quenching; the treatment which dissolves the excess copper (at 780°C) is known as the "solution anneal" and is generally performed at a temperature close to the alloy melting point (above the solid-solubility line). The purpose of this step is to dissolve most of the minor metal (or metals) in the major metal. It is also apparent from Table 1 that the 500°C precipitation treatment for one-half hour causes softening compared to the treatment for the same time at 300°C. Such an effect is called "over-aging."

Since the discovery and early rationalization of precipitation-hardening, much effort has been devoted both to the search for new hardenable alloys and to the understanding of the detailed mechanism of the precipitation processes involved in these alloys. Other aluminum-base alloys, and those based on lead, copper, nickel, iron, magnesium, and titanium have been developed and are commercially available. An even wider variety of alloys has been studied for theoretical reasons. Many of these alloys are applicable to the solution of current material problems and an understanding of them is therefore important to both metallurgists and engineers in general.

This discussion has been primarily concerned up to now with hardness. Precipitation can also be detected by changes in many other properties: heat evolution during the precipitation reaction, appearance of a dispersed second phase as a visible (to either an optical or electron microscope) precipitate; increase (or decrease sometimes) in electrical conductivity; change in lattice parameter of the matrix metal as the solid solution is decomposed; segregation of solute atoms into zones (by x-ray diffraction study of single crystals); change in magnetic properties such as coercive force and Curie temperature; stress-corrosion cracking due to intercrystalline corrosion; ductility; and changes of tensile properties such as yield strength and the elevated temperature stress-rupture strength. All of these effects have been used for the investigation of precipitation-hardening systems, depending on the properties desired in the specific alloy.

The initial stage of the precipitation reaction is the nucleation of a new phase. The very small particles form and grow by chance; some redissolve, but others attain a stable size and continue to grow. The energy barrier to growth and the stable nucleus size depend on the degree of supersaturation (subsequent to the solution-anneal treatment). The stable nucleus size is larger for higher temperatures (at constant composition). Thus, if the nucleation is carried out at a relatively low temperature, and the precipitation temperature is subsequently raised when the rate of particle growth is faster, one can obtain a well dispersed, fine precipitate in a relatively short time. This technique is often used for the precipitation-treatment of some high-temperature alloys where such a structure is considered favorable to good creep-strength at elevated temperatures.

The simple nucleation and growth mechanism is often complicated by the effect of cold work after the solution-anneal and prior to the precipitation-hardening treatment. The internal stress associated with cold work and the preferred orientation of the matrix both influence the ease of nucleation and the rate of particle growth. Certain crystal sites and orientations are favored for the formation and growth of particles. Particles of definite orientation and shape can be detected by both x-ray diffraction and study of the microstructure. The specific orientation is a function of the crystal lattice and relative size of the matrix and the precipitate. Residual stress due to cold work may provide both preferred sites for nucleation (at vacancies or slip planes) and significantly increase

the rate of the precipitation reaction. Cold work is often employed to shorten the precipitation-treatment time in practical alloys. It is also used in conjunction with the heat-treatment to improve spring properties.

Examination of the microstructure of precipitation alloys has revealed useful information about the local heterogeneities of the reaction. The first precipitate to be detected is localized at the grain and twin boundaries. The precipitation reaction is accelerated at the grain boundary; coalescence of precipitate particles may also occur more rapidly at the grain boundaries. This tendency may cause intercrystalline corrosion due to the depletion of the matrix near the grain boundary.

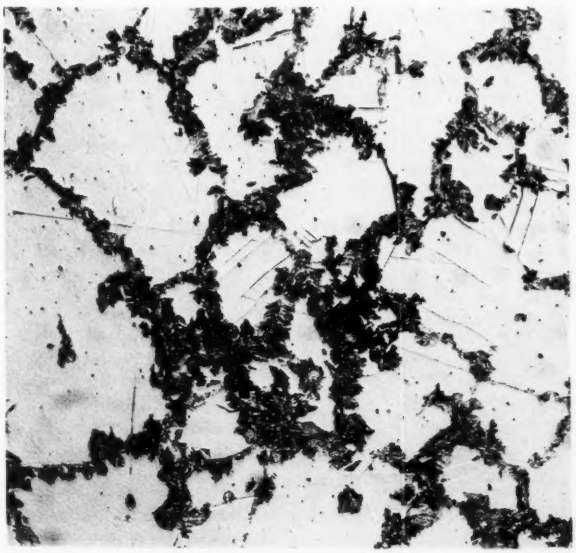
The simultaneous recovery of plastic strain and precipitation may lead to what is known as discontinuous precipitation. In this process, recovered or recrystallized grains replace the deformed ones; the precipitate generally appears in the recrystallized regions. The recrystallization is often accelerated by the strains connected with the precipitation reaction. Figure 2 is a micrograph of a 25 percent cold-worked sample showing the recrystallized regions at the grain boundaries containing unresolved precipitate. This material is a nickel-iron alloy containing titanium; the precipitate is presumed to be a compound of nickel and titanium (Ni_3Ti).

The most recently exploited technique for the investigation of precipitation hardening is the electrolytic extraction of the precipitate by the anodic dissolution of the matrix. If an electrolyte is available in which the matrix dissolves without the precipitate being attacked, the residue remaining after the dissolution can be weighed, identified, and its size distribution determined. If this process is repeated at several stages of precipitation, quantitative data can be obtained on the rate of precipitation and particle coalescence. This technique has been effectively used on various high-temperature alloys where carbides and stable intermetallic compounds are the precipitating phases.

The nature of the interaction between precipitate and matrix and the effect of this interaction on the whole range of physical properties are still controversial subjects. Further clarification of the details of precipitation hardening will contribute to progress in the development of new tailor-made alloys.

Several precipitation-hardenable alloys which are used or are being considered for use by Raytheon for the solution of specific problems are listed below:

1. A magnetron requires a strong, stable permanent magnet to provide a steady magnetic field in the space between the cathode and anode. Alnico V is a permanent magnet material with the best combination of energy product and coercive force of any commercial material. Its exceptional magnetic properties are obtained by heat-treatment in a magnetic field. Alnico V is an alloy of aluminum, nickel, cobalt, copper, and iron. After heat-treatment it is hard and brittle. Precipitation hardening occurs by the separation of a complex phase in the form of plates or rods parallel to the heat-treating field. The large coercive force is the result of the small particle size of the precipitated phase. Alnico V is particularly useful wherever a strong, stable magnetic field is required, as in the case of magnetron magnets (Figure 3).



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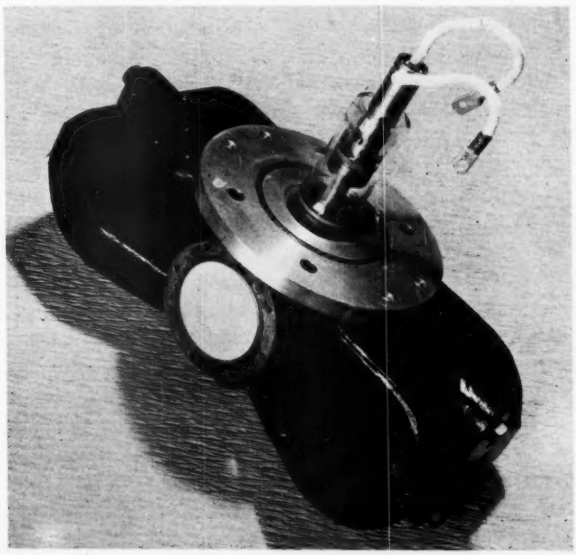

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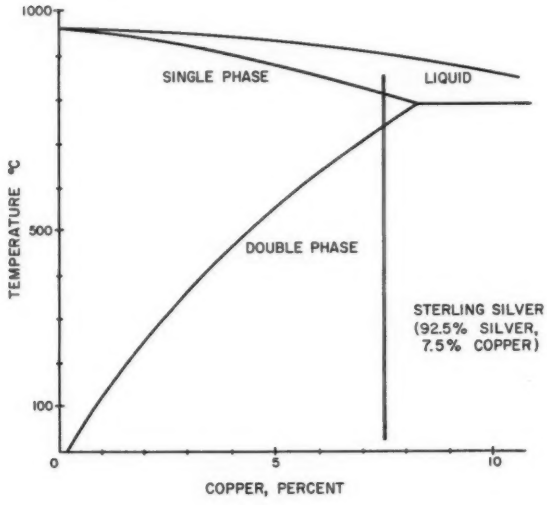

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Examination of the microstructure of precipitation alloys has revealed useful information about the local heterogeneities of the reaction. The first precipitate to be detected is localized at the grain and twin boundaries. The precipitation reaction is accelerated at the grain boundary; coalescence of precipitate particles may also occur more rapidly at the grain boundaries. This tendency may cause intercrystalline corrosion due to the depletion of the matrix near the grain boundary.

The simultaneous recovery of plastic strain and precipitation may lead to what is known as discontinuous precipitation. In this process, recovered or recrystallized grains replace the deformed ones; the precipitate generally appears in the recrystallized regions. The recrystallization is often accelerated by the strains connected with the precipitation reaction. Figure 2 is a micrograph of a 25 percent cold-worked sample showing the recrystallized regions at the grain boundaries containing unresolved precipitate. This material is a nickel-iron alloy containing titanium; the precipitate is presumed to be a compound of nickel and titanium (Ni_3Ti).

The most recently exploited technique for the investigation of precipitation hardening is the electrolytic extraction of the precipitate by the anodic dissolution of the matrix. If an electrolyte is available in which the matrix dissolves without the precipitate being attacked, the residue remaining after the dissolution can be weighed, identified, and its size distribution determined. If this process is repeated at several stages of precipitation, quantitative data can be obtained on the rate of precipitation and particle coalescence. This technique has been effectively used on various high-temperature alloys where carbides and stable intermetallic compounds are the precipitating phases.

The nature of the interaction between precipitate and matrix and the effect of this interaction on the whole range of physical properties are still controversial subjects. Further clarification of the details of precipitation hardening will contribute to progress in the development of new tailor-made alloys.

Several precipitation-hardenable alloys which are used or are being considered for use by Raytheon for the solution of specific problems are listed below:

1. A magnetron requires a strong, stable permanent magnet to provide a steady magnetic field in the space between the cathode and anode. Alnico V is a permanent magnet material with the best combination of energy product and coercive force of any commercial material. Its exceptional magnetic properties are obtained by heat-treatment in a magnetic field. Alnico V is an alloy of aluminum, nickel, cobalt, copper, and iron. After heat-treatment it is hard and brittle. Precipitation hardening occurs by the separation of a complex phase in the form of plates or rods parallel to the heat-treating field. The large coercive force is the result of the small particle size of the precipitated phase. Alnico V is particularly useful wherever a strong, stable magnetic field is required, as in the case of magnetron magnets (Figure 3).

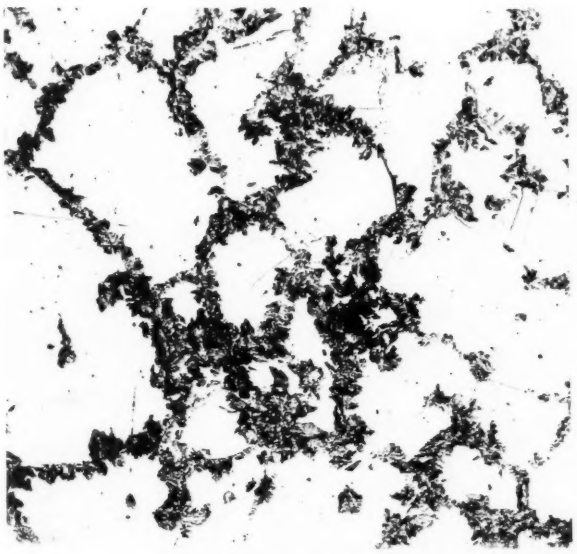


Figure 2

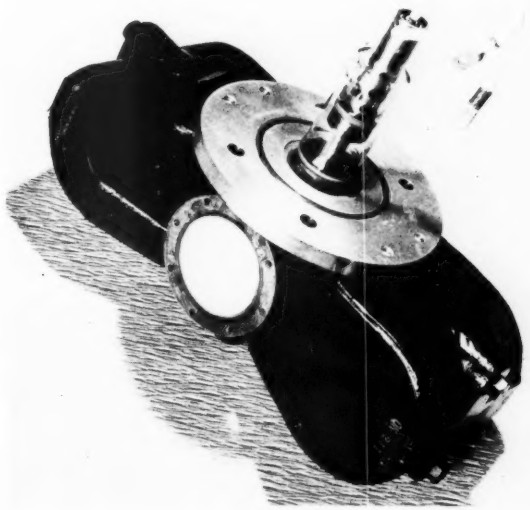


Figure 3

2. Beryllium copper is used for the torsion bar in a rate gyro manufactured by the Missile Systems Division. It is a two percent beryllium, balance copper alloy which combines good electrical conductivity with hardness and strength. It is most useful as a spring material because of its resistance to fatigue and low hysteresis loss. Depending on its temper before the precipitation treatment, this alloy will give tensile strengths ranging from 165,000 to 220,000 psi. Severe cold work before heat-treatment permits the achievement of very low hysteresis loss. In this case, minor changes in heat-treatment can be used to adjust the critical properties of hardness and hysteresis within narrow limits required by the gyro specifications.
3. Phosnic bronze is another copper-base alloy; it is hardened by the precipitation of a nickel-phosphorous phase. This alloy when aged is softer than beryllium-copper, has a higher electrical and thermal conductivity, but retains its strength to a higher temperature than the beryllium-copper. The latter characteristic is advantageous when an application requires an alloy with good conductivity but which does not soften during subsequent heating (such as an outgassing cycle). In fact, the final outgassing cycle can be used to precipitation-harden the alloy.
4. Inconel X is one of several precipitation-hardenable nickel-chromium alloys which can be treated to develop exceptional high temperature fatigue resistance. It was proposed recently for use in a spring contact which was to operate at 350°C. In this case, a spring temper is required before the precipitation treatment.
5. Ni-SpanC is an iron-nickel-chromium alloy which is hardened by the precipitation of a nickel-titanium compound. The precipitation process serves to raise the yield strength of the alloy and to provide a close adjustment of the temperature coefficient of elastic modulus. Removal of nickel from the solid solution by reaction with titanium shifts the Curie point and thereby changes the room temperature slope of the elastic modulus versus temperature curve. The adjustment of this slope close to zero by heat-treatment is a technique employed by the Missile Systems Division in their manufacture of electromechanical filters (Figure 4) with flat frequency versus temperature characteristics.
6. A new alloy with creep resistance at moderate temperatures superior to the conventional aluminum-base alloys is now becoming available for use in missile fabrication. This is a magnesium-base alloy hardened with thorium. It will presumably be applicable to airframes where aerodynamic heating would prevent the use of the aluminum alloys.

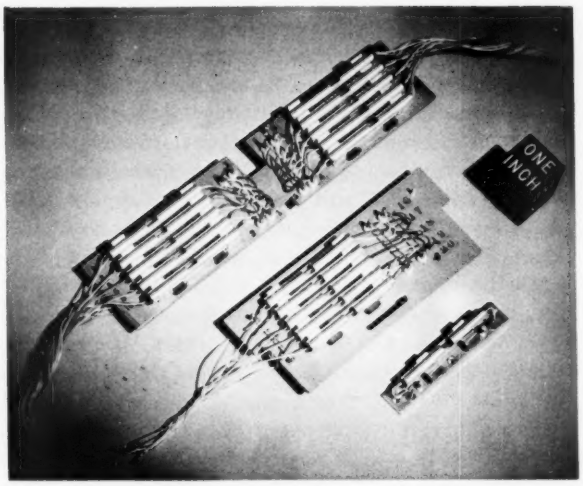


Figure 4

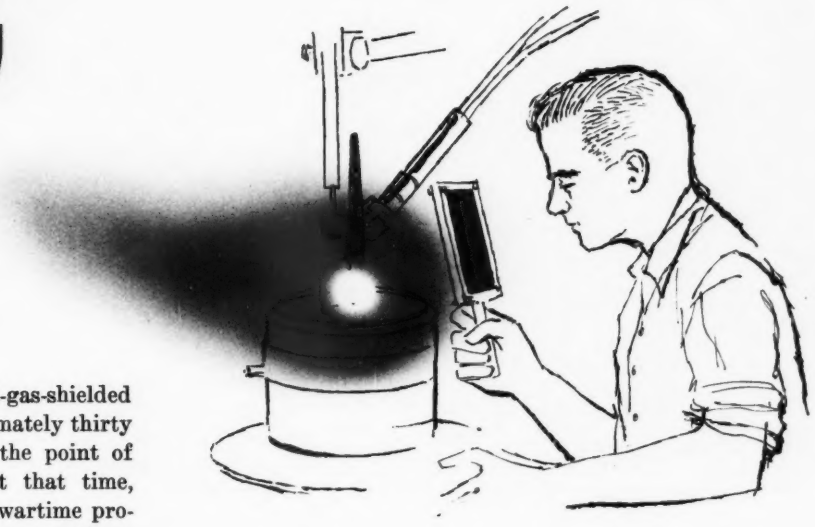
These examples are intended to indicate only a few of the applications of precipitation-hardened alloys. When one considers the very common aluminum-base wrought and cast alloys; the wide range of nickel base alloys (Inconels, Incoloys, Nimonics, Duranickel, Hastelloys) with various additions such as cobalt, chromium and molybdenum; and assorted other alloy systems too numerous to mention — one realizes the universality of the precipitation-hardening principle.

Inventions

Congratulations to the following persons for their valuable contributions to Raytheon's portfolio of inventions:

Name	*Field of Invention*
Joseph Apelbaum William O'Brien	TL-12 Cathode
William Arsenault	Quick Replacement Terminals
Raymond Brien Gerhard Flodberg	Adjustable Stem Trimmer
Ralph Carnevale Harry Letaw, Jr. Theodore Taylor	Semiconductor Domes
Ben Cole Edward Sheldon, Jr.	Cycle Rate Counter
Edward Dench	Magnetron Diode
Edward Dench	Collector for Backward Wave Devices
Edward Downing George Smith	Cathode Support
Stanley Ehrlich	Omnidirectional Beam Pattern
Stanley Ehrlich Paul Frelich	Lightweight Directional Sonar System
Vernon Fisher	Erecting and Seating Device
Paul Frelich	Doppler Navigation System
Peter Kaufmann	Cold Point Probe
John Osepchuk	Traveling-Wave Tubes
Allen Smith	Silicon Carbide Crystals
Charles Staufenberg Donald Ward	Signal Actuated Relay System
Edwin Turner	Doppler Navigator
David White	Operation of Bitermitrons
John Williams	Method of Tinning Molybdenum

HELIARC WELDING



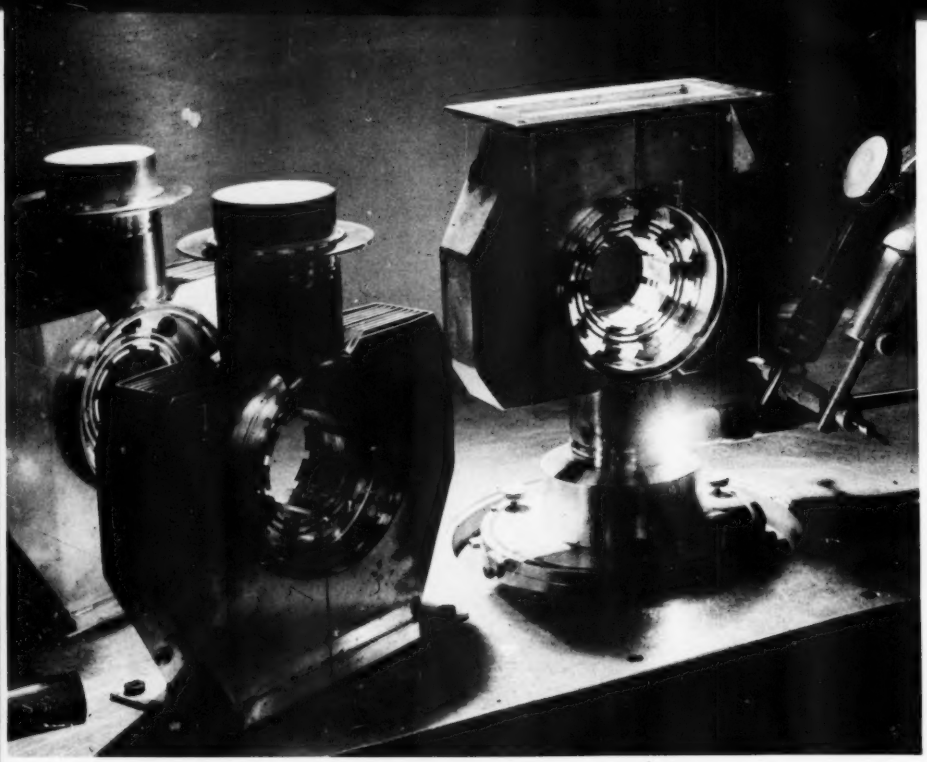
R. R. Garber
Microwave and Power Tube Division

ALTHOUGH the principles of inert-gas-shielded arc welding have been known for approximately thirty years, the process wasn't developed to the point of commercial practicality until 1942. At that time, working under the pressures exerted by wartime production demands, the combined development efforts of the Dow Chemical Company and the Northrup Aircraft Company produced the "Heliarc" welding process used throughout the welding industry today. This form of welding was primarily developed for the joining of magnesium and other previously "hard to weld" metals, such as the aluminum alloys and stainless steels of aircraft fabrication. During the war and in early post-war years the process rapidly expanded in scope to include weld applications to practically all other commercially used metals.

The history of Heliarc welding at Raytheon began approximately six years ago when manufacturing personnel of Microwave Power Tube Research and Development Laboratory recognized the great potential of this process in tube fabrication. An experimental development program was initiated within the laboratory to adapt the Heliarc process to the varied and precise metal-joining requirements of the tube industry. How this welding process has been applied to the manufacture of microwave power tubes and what effect it has had on production techniques, final product cost, and tube quality will be described.

The term Heliarc welding is a trade name which technically refers to two forms of inert-gas-shielded arc-welding processes. One is the metal inert-gas-shielded process and the other is the tungsten inert-gas-shielded process. The metal inert-gas process utilizes a welding electrode which is composed of the desired filler metal and is actually melted and transferred to the weld zone to effect the weld. In the tungsten inert-gas welding process, which is the process introduced by the Microwave Power Tube Research and Development Laboratory, the electrode is tungsten which is not transferred to the weld zone as filler. If filler metal is required with the tungsten process it is added by manipulating a filler rod in the arc (sustained between the tungsten electrode and the work) where it is melted and transferred to the weld zone. Thus, in the Heliarc welding process as generally used in vacuum tube fabrication, the heat of fusion is obtained by an electric arc struck between a tungsten electrode and the work, with a monatomic inert gas shielding provided to exclude atmospheric gases from the weld zone. Helium and argon gases are used exclusively in the application of the tungsten process to tube manufacture.

It is through the use of the virtually nonconsumable tungsten electrode and the inert gas shielding that this welding process applies itself so readily to the manufacturing methods of the tube industry. Utilizing the tungsten electrode we are able to obtain weld fusion zones of higher purity and more consistent density than are available through other arc welding processes. This purity control is established through the elimination of deleterious impurities usually transferred to the weld zone by conventional welding electrodes and filler materials. Since the tungsten is not transferred to the weld puddle, the only impurities which may exist in the fusion zone are those of the parent metal itself. The tungsten electrode also offers a very effective means of precision heat control. Since



only the very tip of a needle-sharp tungsten electrode melts while sustaining the arc, very accurate arc control is available by proper arc gap settings. This is an important feature of Heliarc welding for vacuum tube manufacture because most tube work deals with straight fusion (no filler rod), automatic machine welding and the close control of heat localization is critical to effect vacuum-tight joints consistently.

It is through the use of the inert gas shielding that it is at all possible to apply this welding process to our work. The shielding gas serves several purposes. It serves to exclude the atmosphere from around the arc and weld puddle; it provides a means of initiating the arc on machine welding applications; and it is a cooling medium for cooling the work, the tungsten electrode and other critical torch components during and after the welding cycle.

In excluding the atmosphere from around the arc and weld puddle the inert gas performs its primary function of producing an oxide- and spatter-free weld zone which requires no further cleaning. It is this oxide-free quality that allows us to produce in quantity precision joints that are consistently vacuum-tight without the use of flux. (Elimination of flux is desirable because of the possibility of vacuum contamination.)

A second function of the inert gas is to help start the arc on machine welding setups without the necessity of actual electrode to work contact so common to other welding processes. By superimposing a current of high frequency (1.5 — 2.0 Mc) on the welding circuit, the inert gas is ionized across a preset arc gap, thereby providing a path of low resistance which can be easily breached by conventionally low welding voltages. This high frequency starting arrangement was used originally with alternating current welding where its purpose was to prevent arc-out at zero current points. Since all welding units used at Raytheon in tube development and manufacturing have direct current power supplies, the sole function of the high frequency source is to initiate the arc on machine welding applications. As this frequency falls in or near the broadcast band a cut-out circuit automatically shuts off the unit immediately after the arc has been initiated to prevent excessive rf interference, as well as to prevent breakdown of the welding cable insulation.

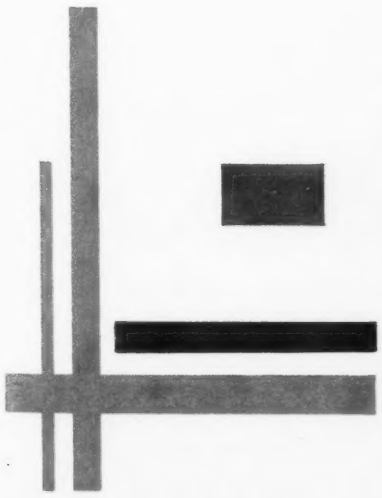
A third function of the shielding gas, i.e., cooling of the work, electrode and torch components, assists again in maintaining quality control of the weld produced. Through adequate cooling of these components during and after the welding cycle subsequent welds are not contaminated with impurities or oxidations produced by improperly cooled torch components.

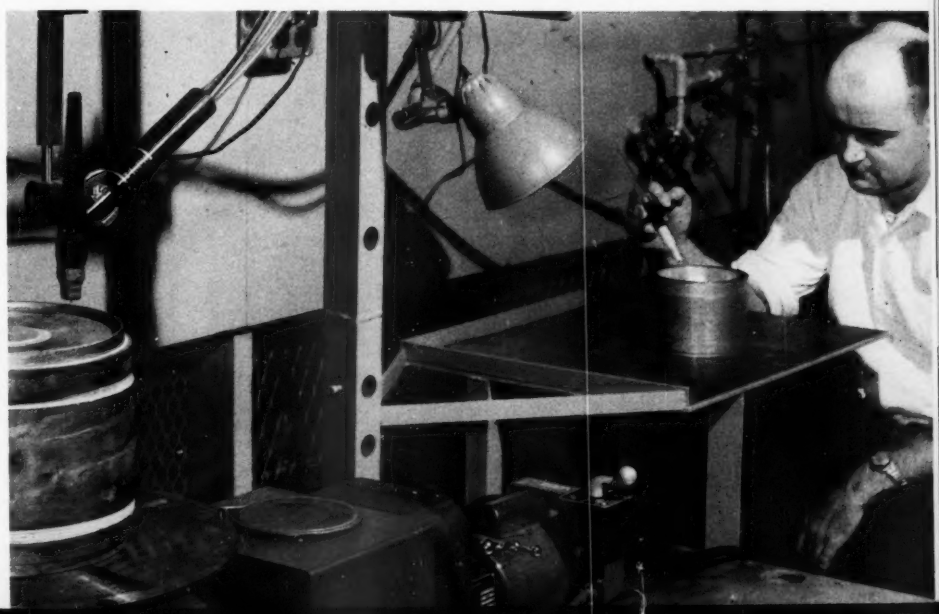
The production of microwave power tubes constantly poses metal joining problems involving most of the known pure metals and alloys. The major problem confronting the production engineer in the construction of a typical magnetron, which may contain close to a dozen different metals and alloys, is to join these various materials both to themselves and to each other. These metal joining processes must be applied in such a manner as to produce a final tube structure which meets all of the complex and precise electrical, mechanical and vacuum requirements necessary for proper operation. The process must also meet the rigid requirements of expedient production methods.

Prior to the advent of Heliarc welding at Raytheon all metal joining on microwave power tubes was achieved through brazing — except, of course, in the case of the mechanical-electrical joints of resistance welding. The all-brazed version of tube construction utilizes numerous and varied brazing methods, such as furnace, induction heating, torch and resistance brazing.

Each of these brazing techniques has its own attributes and specific application advantages and each is essential to present day tube manufacture. However, the all-brazed version of tube construction has a rather imposing and formidable disadvantage for large scale production. The extensive range of brazing temperatures associated with the building of a typical magnetron includes the low melting temperature of soft soldering operations (200°C) and the high sintering temperatures of the more refractory brazing compounds of molybdenum (2200°C). This extremely wide temperature range, along with the precision temperature control required at intermediate temperatures, prohibits the use of any universal brazing system. These temperature requirements plus other basic metal joining considerations such as atmosphere control, facility capacity, adaptability, jigging and cleanliness requirements necessitate the maintaining of a large variety of complex and expensive brazing equipments. Heliarc welding cannot be considered a panacea for all brazing difficulties. It is worthy to note, however, that with a relatively low initial cost and a low subsequent maintenance cost the complete range of temperature requirements for tube fabrications can be realized with a single installation of Heliarc welding equipment.

This versatility of temperature control is especially useful in the fabrications of tube structures composed of the high refractory metals. The high brazing temperatures encountered in the joining of refractory structures have necessitated relatively expensive jigging. Such high temperature brazing operations have always presented problems in the production of consistent quality assemblies. This jigging problem poses a decided disadvantage which is especially severe in tube development programs where experimental tube design change may make many of these expensive brazing jigs obsolete before constructional details are fixed. Heliarc tack or plug welding has proven invaluable for such cases. It has replaced the sintering process entirely in many instances. Tungsten and molybdenum cathode structures of several tube types are now of a completely welded design. Since molybdenum weldments are inherently brittle, due to the great sensitivity of molybdenum to trace impurities, design precautions must be taken to prevent any structural stresses from being developed in the actual weld metal. Through good structural design engineering and weld joint designing, several all-welded cathode





structures have passed rigid vibration and shock test specifications. This inherent brittleness of molybdenum is due to its affinity for oxygen, of which 0.0001% content will produce detrimental embrittling effects to the weld fusion zone. It is only because of the extreme purity of the shielding gas atmosphere provided the weld zone that the oxygen absorption can be kept at the minimum already contained in the base metal. For this reason thrice-melted arc vacuum-cast molybdenum is preferred for welded tube structures. Because of this extremely critical weld embrittlement, all molybdenum weldments of tube structures are restricted to mechanical-electrical joints, and are not applied to vacuum joint applications. Figure 1 is a photomicrograph of a cross section of a typical Heliarc weld for an all molybdenum cathode structure. Note normal grain growth in the weld zone, the uniform density and the lack of porosity obtained.

The foremost problem encountered by weld engineering in effecting the transition from brazing to welding in tube applications is the necessary joint redesign. Since the major part of metal joining problems encountered in tube work involves the pure metals and alloys, the welding engineer is constantly faced with strength of weld difficulties. Fusion zones of pure metal weldments are basically cast metal and are inherently weak. Unlike the characteristic grain refinement and subsequent strengthening obtained by heat treating the ferrous alloys, the grain structure of the non-ferrous pure metals experience grain growth and the associated loss of parent metal strength, particularly when subjected to the elevated temperatures of tube bake-out.

For this reason it can be seen that it is imperative to maintain utmost cleanliness during all part fabrications to minimize the inclusion of weakening impurities. It is important to eliminate all contaminations of the weld metal caused by direct pickup or through vaporization of surface impurities in close proximity to the weld. Such impurities as oil, grease, scale, oxides or other foreign matter introduced into the fusion zone of pure metals and non-ferrous alloy welds invariably result in porous and embrittled weldments. Figure 2 shows a photomicrograph of an oxygen-free high-conductivity copper weld which was made over a supply of oil and grease. As shown by the voids and general porosity, achievement of vacuum-tight joints is highly improbable. These voids are caused by the gas evolved by the vaporization of the impurities in and around the weld zone. The expanding gases evolved disrupt the protective shielding gas atmosphere, thus further contaminating the weld metal by admitting atmospheric gases to the molten weld metal. Another example of improper shielding gas coverage is displayed in Figure 3. This weld was made again on oxygen-free high-conductivity copper with an experimental gas mixture of argon and hydrogen. This photo compared to that of Figure 4 (a typically sound copper weld obtained with the proper shielding gas of helium) emphatically indicates the

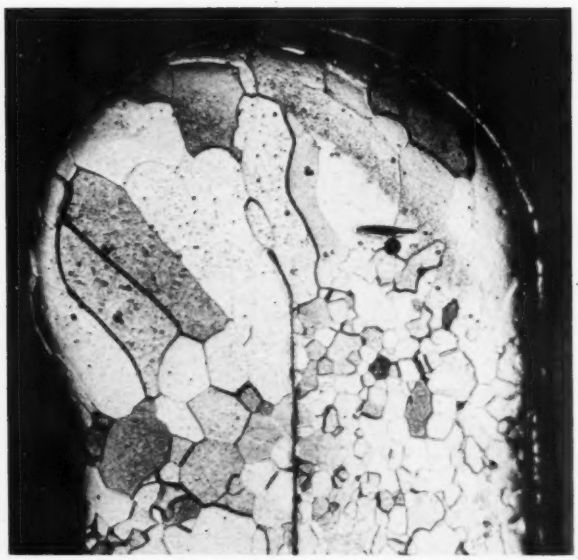


Figure 1

Figure 2

necessity of proper gas coverage to produce sound copper welds.

Figure 5 shows voids produced by welding over an oxide deposit commonly developed by unsatisfactory welding conditions such as low surface speeds, excessive current, or insufficient gas flow and coverage. This particular weld was made on a circular cupronickel assembly and the voids lie at the weld termination which overlaps the beginning of the weld. In this instance, these voids are of little consequence to the vacuum-tightness or strength of the weld, as sufficient penetration of sound weld metal exists below the voids. However, the external appearance of the weldment is marred by surface discontinuities produced by the voids. This condition is rectified by providing proper gas coverage and modifying welding conditions so that the weld is terminated before surface oxides can be formed to a harmful extent.

It is impossible to describe here all of the advantages and applications found for the highly versatile fabrication process of Heliarc welding. Only a few noteworthy applications have been cited, representative of countless other metal joining problems which have been resolved at Raytheon by Heliarc application during the past six years. The process has greatly reduced the cost of tube manufacture by substantial reductions in assembly time and handling, simplification and elimination of jig requirements, and the utilization of less expensive processing equipments.

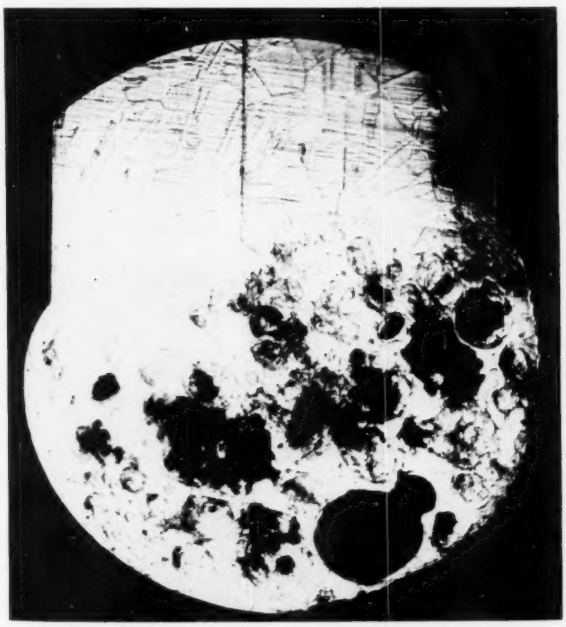


Figure 3

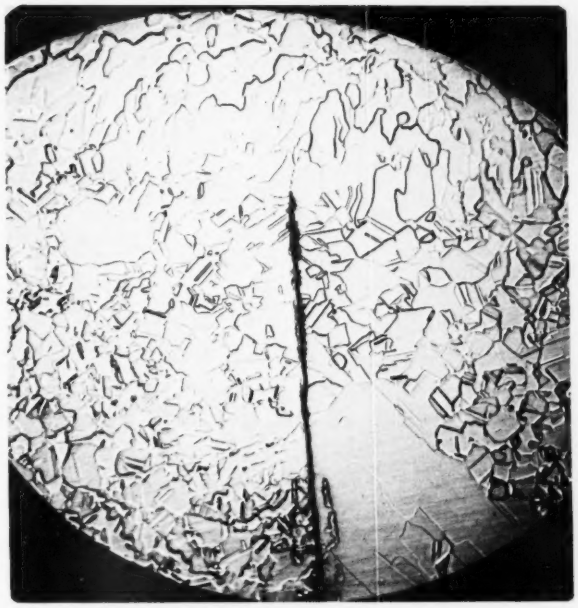


Figure 4

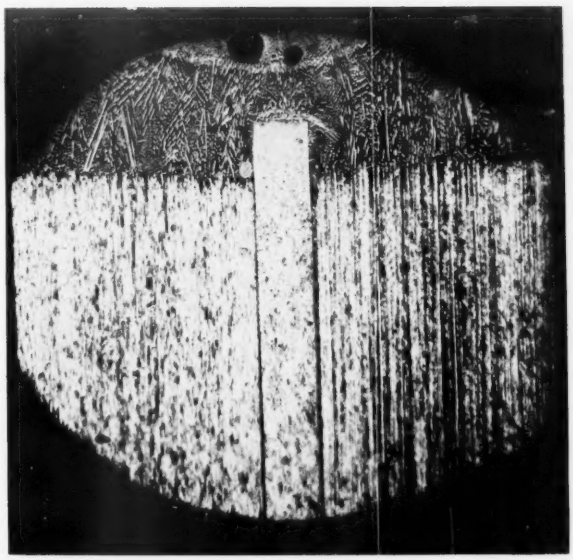


Figure 5

How reliable Raytheon electronics protects you— every mile you fly

Through storm and darkness, fog and snow, U.S. airlines are setting major reliability records—the result of skilled men using trustworthy equipment.

The weather radar in your airliner's nose, the radio that keeps in contact with the ground, and the automatic pilot—all use Raytheon electron tubes, including special types developed for the airlines.

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